Study on CO_2 Absorption in Single MEA and Mixed MEA & DEA

By

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Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

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CERTIFICATION OF APPROVAL

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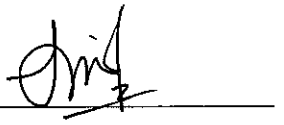
Approved by,



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January 2005

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Foo Lee Lian

FOO LEE LIAN

ABSTRACT

The overall effect of greenhouse warming caused by increasing amount of carbon dioxide (CO_2) in the atmosphere has lead to growing interest in research for new methods to reduce the CO_2 emissions. One such alternative is to recover CO_2 from flue gas by chemical absorption with alkanolamines, which can be then used for CO_2 sequestration. Alkanolamines have long been used for removing CO_2 and hydrogen sulfide (H_2S) from natural gas streams. The classes of alkanolamines are divided into primary amines (monoethanolamine, MEA), secondary amines (diethanolamine, DEA) and tertiary amines (monodiethanolamine, MDEA). The objectives of this study are to study the effect of solvent flow rate and amine concentration in effective CO_2 removal as well as to recommend optimum percentage of mixed primary and secondary amines for efficient CO_2 absorption. The use of mixture of primary and secondary amines would maximize the individual properties of the single amines. The experiment was conducted in a wetted wall gas absorption column with various MEA concentrations, varying solvent flow rate and varying mixtures of amines. From the experiment, the effect of increasing solvent flow rate would lead to overall better CO_2 removal. For solvent concentration, an increase of amine concentration would increase the maximum overall CO_2 removal efficiency. The optimum blend of amines from this study is reported as DEA-25wt% and MEA-10.2wt% based on the maximum total moles of CO_2 effectively removed with this blend. From this study, the main factor which drives the CO_2 absorption process in a mixed amine system is the concentration of MEA in the mixture. A decrease in MEA concentration would lead to a decrease in the total moles of CO_2 removed.

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ABBREVIATION

CO_2	Carbon Dioxide
MEA	Monoethanolamine
DEA	Diethanolamine
MDEA	N-methyldiethanolamine
DGA	Diglycolamine
DIPA	Diisopropanolamine
H_2S	Hydrogen sulfide
HCO_3	Hydrogen carbonate
COS	Carbon Oxysulfide
CS_2	Carbon Disulfide
O_2	Oxygen
IR	Infrared
wt%	Weight percentage
vol%	Volume percentage
N_2	Nitrogen

NOMENCLATURE

$\mathbf{K_G}$	Overall gas film mass transfer
P	Bulk gas partial pressure
P^*	Equilibrium partial pressure
H	Henry's Constant
P_i	Partial pressure at gas liquid interface
k^0_L	Liquid film mass transfer coefficient
E	Enhancement factor
$[CO_2]$	Concentration of CO_2
k_l	Pseudo first order rate constant
a	Specific surface area

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Carbon dioxide is considered to be a major greenhouse gas, causing the temperature of the atmosphere to rise. Global warming caused by increasing emissions of gases such as carbon dioxide, methane, chlorofluorocarbon, carbon dioxide and nitrous oxide is considered a serious environmental problem. Among these gases, CO_2 has the greatest adverse impact on the observed greenhouse effect causing approximately 55% of the observed global warming (IPCC, 1990). Therefore the reduction of CO_2 emissions from fossil fuel energy systems is a growing issue.

This greenhouse effect could cause dramatic global climatic and environmental changes in precipitation and storm patterns as well as increase in sea level. This problem has a significant impact on the world's environment and the increase in atmospheric CO2 has primarily resulted from the consumption of fossil fuels for energy. The reduction of CO_2 emissions from fossil-fueled energy systems is considered to be a growing important issue in reducing the global warming trend. Awareness to the CO_2-mediated global warming problem has lead to several international forums on climatic changes to be called by the United Nations. The latest one held in Kyoto, Japan toward the end of 1997 required that the amount of CO_2 discharged by industries in all developed countries be reverted to the 1990 standards by 2001 (Shenh and Ching.,1999).

The removal of CO_2 from the industrial flue gases is necessary to mitigate the global warming problem. The various technologies developed for CO_2 removal includes;

absorption by chemical solvents, physical absorption, cryogenic separation, membrane separation, CO_2 fixation by biological or chemical methods, and O_2/CO_2 combustion. From these current alternatives, CO_2 absorption by chemical solvents seems to offer a practical alternative. In fact, CO_2 absorption by alkanolamines has been the most popular and effective method with much extensive research performed in the recent decades. The main area of research done was on the chemical reaction mechanism, mass transfer, gas/liquid equilibrium and other related aspects of CO_2 absorption.

The process of CO_2 absorption with alkanolamines is an example of chemical absorption where a reversible chemical reaction takes place in the liquid phase. Chemical reactions can increase the rate of absorption, increase the absorption capacity of the solvent, increase selectivity to preferential dissolve only certain components of the gas. Chemical absorption is the most suitable method for the separation of CO_2 from exhaust gases, when carbon dioxide has a low concentration (5-15% by volume) in a gaseous stream at atmospheric pressure. There are several small commercial facilities in the U.S that use 15 to 30-wt% monoethanolamine (MEA) to recover CO_2 from coal-fired power plants and gas turbines (Chapel et al., 1999; Sander and Mariz, 1998).

1.2 PROBLEM STATEMENT

Alkanolamines absorption is an important technological option for CO_2 sequestration to address the global warming problem. Alkanolamines have long been used commercially for removing CO_2 from natural gas and hydrogen. However, the applications of alkanolamines to treat combustion coal gases must address lower CO_2 partial pressure, solvent degradation by oxygen and large gas flow rates.

The growing interest among researchers is to discover an optimum blend of mixed amines that can effectively remove CO_2 better in comparison with single amines systems.

The optimum blend of the mixed amines should have a high CO_2 absorption capacity and lower regeneration requirements to save energy cost on the stripper side.

1.3 OBJECTIVE AND SCOPE OF STUDY

The primary focus of the project is to discover the effectiveness of alkanolamines as solvent in absorbing CO_2 as well as to compare the performance of primary and secondary alkanolamines. This project also aims to determine the optimum percentage of amine mixture for effective CO_2 absorption.

The scope of this study would include the effect of solvent flow rate, solvent concentration and the mixtures of primary amine (MEA) and secondary amine (DEA) on maximum overall CO_2 removal efficiency as well as comparison of CO_2 absorption capacity for varying concentrations of MEA.

For this study, the effect on the selection of amines, properties of primary and secondary amines will be used to explain the absorption properties of the solvent. The absorption occurring is assumed to be that of physical absorption which depends solely on liquid film mass transfer coefficient.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Absorption theory

Absorption process involves a process whereby a gas mixture is contacted with a liquid, which acts as the absorbent or solvent to selectively remove one or more components, by mass transfer from the gas to the liquid. For this study, the CO_2 gas is the solute or absorbate whereas the amine solvent is the absorbent. Absorption is mainly used in chemical processes to separate gas mixtures, to remove impurities, contaminants, pollutants or catalyst poisons from a gas and to recover valuable chemicals from a bulk stream. The opposite of absorption is termed as stripping wherein a liquid mixture is contacted with a gas to selectively remove components by mass transfer from the liquid to the gas phase.

Absorption can be classified into either physical absorption or chemical absorption.
Physical absorption can be termed as when water and hydrocarbon oils are used as absorbents and no significant chemical reactions occur between the absorbent and the solute. This differs from chemical absorption whereby as an example, aqueous sodium hydroxide (a strong base) is used as the absorbent to dissolve an acid gas. This absorption is accompanied by an irreversible neutralization reaction in the liquid phase and the process is referred to as chemical absorption or reactive absorption. The more complex examples of chemical absorption are processes for absorbing CO_2 and H_2S with aqueous solutions of monoethanolamine (MEA) and diethanolamine (DEA), where a reversible chemical reaction takes place in the liquid phase.

2.2 Wetted wall gas absorption process

For this study, a wetted wall gas absorption column is used. The solvent flow is from the top of the column and a minimum thickness of flow is maintained on the surface wall of the column. The gas flows countercurrently from the bottom of the column to the top of the column. Hence, the overall transfer between the gas and solvent occurs at the surface of the wetted wall.

2.3 Theory of mass transfer

According to Rochelle and Mshewa (2004), the two-film theory of gas/liquid mass transfer usually represents flux by using mass transfer coefficients and driving forces defined in one of several ways. The overall gas film mass transfer, K_G uses the bulk gas partial pressure, P_{CO2} and the equilibrium partial pressure over the bulk solution, P^*_{CO2}:

$$\text{Flux} = K_G (P_{CO2} - P^*_{CO2}) \quad (1)$$

Equilibrium CO_2 partial pressure, P_{CO2} and the concentration of undissociated CO_2 $[CO_2]$ are related by the thermodynamic Henry's Constant:

$$P_{CO2} = H_{CO2} [CO_2] \quad (2)$$

Therefore overall gas phase mass transfer can also be represented by:

$$\text{Flux} = K_G H_{CO2} ([CO_2]^* - [CO_2]) \quad (3)$$

Flux can be calculated from the gas film mass transfer coefficient, k_g in terms of the difference between the CO_2 partial pressure at the gas liquid interface, P_{CO2i} and P^*_{CO2}:

$$\text{Flux} = k_g (P_{CO2i} - P_{CO2}^*) = K_G H_{CO2} ([CO_2]^*_i - [CO_2]) \quad (4)$$

Flux can also be calculated from a liquid film mass transfer coefficient, k°_L using the overall solubility of CO_2 as the driving force:

$$\text{Flux} = k^\circ_L([CO_{2total}]_i - [CO_{2total}]) \quad (5)$$

CO_{2total} refers to the sum of all CO_2 species, including free CO_2 bicarbonate (HCO_3^-), carbonate (CO_3^-) and carbamate.

The liquid film flux can also be represented using an enhancement factor, E with the concentration of free CO_2 as the driving force:

$$\text{Flux} = k^{o}_{L}E([CO_2]_i - [CO_2]) \quad (6)$$

The enhancement factor accounts for the effect of both fast and instantaneous equilibrium reactions on the absorption of CO_2. The five limiting mechanisms that play a role in CO_2 absorption are as reported in the following table according to Rochelle and Mshewa (2004).

Table 2.1: Mechanism of CO_2 absorption/desorption in aqueous amine solutions

Mechanism	$K_G H_{CO2}$ (m/s)
Bulk reaction	$\frac{k_l}{a}$
Absorption with fast reaction	$\sqrt{k_L^{o\,2} + k_l D_{CO2}}$
Physical absorption	k^{o}_{L}
Fast reaction	$\sqrt{k_l D_{CO2}}$
Instantaneous reaction	$k^{o}_{L} \frac{d[CO_{2total}]}{dP^{*}CO_2} H_{CO2}$
Combined mechanism	-

Notation:

k_l= pseudo first order rate constant, s^{-1} dependent on amine type, concentration and temperature

k^{o}_{L} = liquid film mass transfer coefficient, m/s

a = specific surface area, m^2/m^3 liquid holdup

$HCO_2 = \frac{P^{*}CO_2}{[CO_2]^{*}}$ bar-m^3/kmol

$\frac{d[CO_{2total}]}{dP^{*}CO_2}$ = slope of equilibrium curve, kmol/m^3 bar dependent on loading, types of amine and concentration.

A bulk reaction is not the limiting factor or important mechanism in the CO_2 and amine system. The K_G depends on the reaction rate constant, k_l and the specific surface area of the solution, a. The K_G for a bulk reaction is always larger than that of any other mechanism and therefore is not a significant limiting factor.

Physical absorption can be a controlling mechanism for amine systems with smaller rate constants for CO_2. The K_G depends on the liquid film mass transfer coefficient, but it is independent of the reaction kinetics. Even though physical absorption still occurs in the bulk solution, it plays an important role in reducing the CO_2 vapor pressure of the solution.

Fast reaction is an important mechanism in most amine/CO_2 systems. The simplified expression in Table 2.1 was concluded to be dependent on rate constant and is independent of the liquid film mass transfer coefficient.

Instantaneous reaction can become limiting with faster kinetics such as those in pure DEA at stripper temperature. At this limiting condition the K_G is related to the liquid film mass transfer coefficient for the amine and CO_2 reaction products as well as to the slope of the gas/liquid equilibrium curve for the amine solution.

In solutions with high reactivity and very high capacity, which is not typical of CO_2/amine systems, mass transfer may be controlled by gas film mass transfer. The overall gas film mass transfer coefficient will be equal to the simple gas film coefficient, k_g.

2.4 History of amines

Amines are a common absorbent used in the chemical solvent method. Industrially important amines for this operation are primary amines such as monoethanolamine (MEA), the secondary amines such as diethanolamine (DEA) and tertiary amines such as N-methyldiethanolamine (MDEA).

The use of mixed amine systems in gas treating processes is of increasing interest today. The mixed amine systems, which combine the higher equilibrium capacity of the tertiary amine with the higher reaction rate of the primary or secondary amine can bring about considerable improvement in gas absorption and great savings in regeneration energy requirements (Hagewiesche et al., 1995). Sterically hindered amines have also been introduced as a new commercially attractive absorbent over conventional amines such as MEA and DEA. Steric effects adversely influence the stability of the carbamates formed by these amines with CO_2. Due to the instability of the hindered amine carbamates, these readily undergo hydrolysis, forming bicarbonate and releasing free amine, which again reacts with CO_2. This leads to a stoichiometric loading of 1 mol of CO_2 per mole of amine, which is much higher than the conventional primary and secondary alkanolamines.

MEA scrubbing is so far the most acceptable chemical solvent method to react with CO_2. The MEA scrubbing is widely used in the chemical engineering process of gas purification. The chemical reactions have been described by Kohl and Riesenfeld (1985) and Hendriks et.al. (1989):

$$C_2H_4OHNH_2\ (l) + CO_2\ (g) + H_2O\ (l) \leftrightarrow C_2H_4OHNH_3^+(aq) + HCO_3^-(aq) \qquad (7)$$

However current practices of applying MEA solvent to remove CO_2 from flue gas have found their limitations (Xu et al., 1991; Molburg et al.,1994). The limitations are that

MEA solvent has a low absorption capacity for CO_2. MEA solvent is also easily oxidized by oxygen and can form irreversible byproducts thus reducing the reaction rate of the absorption process. The MEA solvent absorption capacity is thus lowered. This makes the solvent more difficult to be recovered.

Wolesky et al. (1994) has addressed the problems associated with MEA solvent and suggested future research efforts should be directed toward development of better solvents for removal of CO_2. An ideal solvent should have at least two desirable characteristics, which is an ideal capacity of one unit weight of CO_2 absorbed per unit weight of solvent. The recovery of solvent should also be at relatively lower temperature to reduce the energy requirement at the stripper side.

2.5 Chemical reaction of amines with CO_2

Amines act by chemical affinity due to their basic character. Monoethanolamine(MEA), diethanolamine (DEA), diglycolamine(DGA), diisopropanolamine(DIPA) and methyldiethanolamine(MDEA) are commonly used to sweeten natural gas. The prefix "mono," "di" or "tri" indicates the degree of substitution around the nitrogen atom. Thus if R denotes the functional group $HOCH_2CH_2$-, monoethanolamine has the chemical formula RNH_2, diethanolamine R_2NH and triethanolamine R_3N.

According to Rochelle and Mshewa (2001), reaction of H_2S with aqueous alkanolamines proceeds through an essentially instantaneous mechanism of proton transfer. Carbon dioxide reacts at a finite rate with alkanolamines making liquid phase mass transfer the controlling step. The CO_2 reaction rate varies with alkanolamine and forms the basis of selection of solvents for a given application: bulk removal of acid gases or selective removal of H_2S.

2.5.1 Reaction between primary amine and H_2S

$$2RNH_2 + H_2S \leftrightarrow (RNH_3)_2S \quad (8)$$

$$(RNH_3)_2S + H_2S \leftrightarrow 2RNH_3HS \quad (9)$$

Generally, these reactions are direct and fast. It is the fastest with monoethanolamine.

2.5.2 Reactions between amines and carbon dioxide

Formation of carbonate and bicarbonate

$$2RNH_2 + CO_2 + H_2O \leftrightarrow (RNH_3)_2CO_3 \quad (10)$$

$$(RNH_3)_2CO_3 + CO_2 + H_2O \leftrightarrow 2RNH_3HCO_3 \quad (11)$$

Formation of carbamate

$$2RNH_2 + CO_2 \leftrightarrow RNHCOONH_3R \quad (12)$$

Reactions (10) and (11) are slow because carbon dioxide must form carbonic acid with water which is a slow reaction before reacting with the amine. Reaction (12) which predominates with monoethanolamine (MEA) is relatively fast.

2.5.3 Reactions between DEA and carbon dioxide

DEA has a fast rate of reaction with CO_2. For this reason, it has commonly been used for bulk removal of acid gases. The heat of absorption is typically about 16kcal/mole (Kohl and Riesenfeld, 1985). Literature data on CO_2 reaction kinetics with DEA is extensive (Glasscock et al.,1989). There is an agreement that the reaction is first order with respect to CO_2. However, there are differences in opinion as to the order of reaction with respect to DEA. Blauwhoff et al. (1984) showed that a hypothesized mechanism for carbmate formation involving the formation of an intermediate zwiterrion confirms most of the data in literature. Glasscock et al. (1990) introduced reversibility into this mechanism which must be included to account for both absorption and desorption. The zwitterions mechanism is presented in two steps:

$$CO_2 + R_2NH \Leftrightarrow R_2NH^+CO_2^- \quad (13)$$

$$R_2NH^+CO_2^- + B_i \Leftrightarrow R_2NCO_2^- + B_iH^+ \quad (14)$$

In the first step a zwitterions is formed by reaction between CO_2 and DEA and protonated DEA is formed in the second step by an abstraction of a proton. B_i designates any species in solution that can act as a base to abstract the proton from the zwitterions in the second reaction step. This species can either be DEA, MDEA or water.

2.6 Applications of amines in industry

2.6.1 Monoethanolamine

Monoethanolamine(MEA) is used in solutions with concentrations of 10-15% by weight. It is very reactive, and absorbs hydrogen sulfide and carbon dioxide simultaneously. The H_2S content can thus be reduced to a few parts per million. However, MEA reacts irreversibly with COS, CS_2 and mercaptans. Its relatively high vapor pressure causes greater losses compared with the other amines. For these reasons, it is mainly used for intensive purification, with fairly low H_2S concentration for a gas containing no COS or CS_2.

2.6.2 Diethanolamine

Diethanolamine (DEA) helps to overcome the limitations of MEA, and can be used in the presence of COS and CS_2. The application of DEA to natural gas processing was described for the first time by Berthier in 1959 (Kohl and Riesenfeld,1985).

2.6.3 Sterically hindered amines

Research aimed to improve H_2S/CO_2 selectivity has led to the development of sterically hindered amines. These amines have functional groups, which by a steric effect prevents the formation of carbamate and thus slows down the absorption of CO_2 without preventing the reaction with H_2S (Weinberg et. al., 1983).

2.7 Advantages of amines

Secondary amines have an advantage as compared to primary amine. Secondary amines have lower heat of reaction with carbon dioxide. Therefore, the secondary amines

require less heat in the regeneration step than primary amines. This is an important consideration from the view of overall energy consumption. On the other hand, tertiary amines react slower with carbon dioxide as compared to primary and secondary amines thus requiring higher circulation rate of solvent to remove carbon dioxide. However, a major advantage of tertiary amine is their lower heat requirement for carbon dioxide liberation from the solvent. The table below displays data for the heat of reaction between the different types of amine and carbon dioxide

Table 2.2: Heat of reaction between amines and CO_2

Types of amine	MEA	DEA	MDEA
ΔH_f for carbon dioxide (calorie/g)	455	360	320
ΔH_f for carbon dioxide (BTU/lb)	820	650	577

Tertiary amines have shown fewer tendencies to form degradation products in use than primary and secondary amines. In addition, tertiary amines have lower corrosion rates compared to primary and secondary amines.

Table 2.3: Physical properties of amines

Table 7.5
PHYSICAL PROPERTIES OF AMINES

	MEA	DEA	TEA	MDEA	DIPA	DGA
Overall chemical formula	C_2H_7NO	$C_4H_{11}NO_2$	$C_6H_{15}NO_3$	$C_5H_{13}NO_2$	$C_6H_{15}NO_2$	$C_4H_{11}NO_2$
Molecular weight (kg/kmol)	61.08	105.14	149.19	119.17	133.19	105.14
Melting point (°C)	10.5	28.0	22.4	−23.0	42.0	−12.5
Boiling point at 101 325 Pa (°C)	170.6	269.2	360 (decomp.)	247.4	248.9	221.3
Specific gravity (20°C/20°C)	1.0179	1.0919 (30°C/20°C)	1.1258	1.0418	0.9890 (45°C/20°C)	1.0572
Absolute viscosity at 20°C (Pa·s)	0.0241	0.3800 (30°C)	1.0130	0.1010	0.198 (45°C)	0.0400 (15.6°C)
Specific heat at 15.6°C (J/kg·K)	2546 (20°C)	2512	2934	2238	2889 (30°C)	2391
Flash point (°C)	93.3	137.8	185.0	126.4	123.9	126.7

Source: after GPSA, 1980, Kohl and Riesenfeld, 1985.

Corrosion is a major concern in amine processes. Generally, alkanolamines is not directly corrosive to carbon steel. The primary corroding element is the dissolved CO_2 in the amines. Therefore, the alkanolamines indirectly influence corrosion rate due to its absorption of CO_2. The observed corrosivity of alkanolamines to carbon steel is generally in the order of the following:

Primary Amines > Secondary Amines > Tertiary Amines

Hindered amines are of growing interest in specialty types of amines for specific purpose. Hindered amine concept is based on the reaction rates of the acid gases with different amine molecules. In the case of CO_2 removal, the capacity of the solvent can be greatly enhanced if one of the intermediate reactions, i.e the carbamate formation reaction can be slowed down by providing steric hindrance to the reacting CO_2. This hindrance effect can be achieved by attaching a bulky substitute to the nitrogen atom of the amine molecule. Besides slowing down the overall reaction, the bulkier substitutes give rise to less stable carbamates. (Wong and Bioletti, 2002) Theoretically, the unstable amine carbamates can double the capacity of the solvent (Chakma, 1994).

2.7 Acid gas removal system with alkanolamines

Hydrogen sulfide, H_2S and carbon dioxide, CO_2 are the main acid gases which have to be removed from natural gas. The specifications on acid gas contents are imposed by safety requirements (very high toxicity of hydrogen sulfide), transport requirements (need to avoid corrosion and crystallization in the case of liquefaction) and distribution specifications(commercial gas).Acid gas removal is a very important industrial operation that has been described in many works.

Various amines are used, but the basic processing diagram always involves contacting the gas with the solvent in an absorption column. The solution is regenerated, after heat exchange and filtration in a distillation column. For a unit operating with DEA, the reboiling temperature is about 133°C. Before being sent to the processing unit, the crude

gas goes through the separator in which the solid and liquid particles, which tend to favor foaming, are removed.

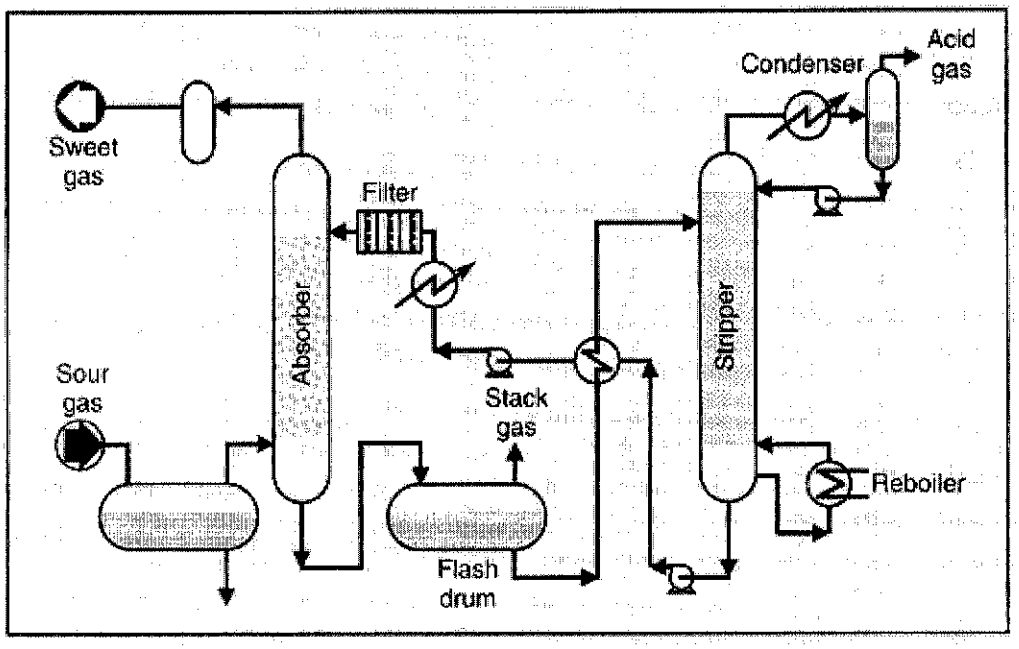


Figure 2.1: Acid gas removal by amine scrubbing

Figure 2.1 depicts the operation of a typical amine based absorption plant for recovery of CO_2 from flue gas. Prior to CO_2 recovery, the flue gas typically needs to be cooled and treated for particulates and other impurities such as SO_x and NO_x to tolerable levels. A feed blower can provide necessary pressure for the pretreated flue gas to overcome the pressure drop in the absorber. Flue gas is passed into the absorption column which typically operates within the temperature range of 40-45°C at the top and 50-60°C at the bottom. The flue gas and lean amine solution contact each other in a countercurrent direction in the absorber. The amine selectively absorbs CO_2 from the flue gas by chemically reacting with it. Small amounts of oxygen O_2 physically dissolve in the amine solution. The CO_2 rich amine solution from the bottom of the absorber is pumped to the flash drum. The rich amine saturated with CO_2 is heated to about 105°C by means of the regenerated or lean amine solution. The heated CO_2-rich amine the enters the upper section of the stripper, which typically operates at a temperature of 110°C at the top and 120°C at the bottom. Operating pressure at the bottom of the column and in the reboiler is typically around 30 psia. Pressure drop across the column is about 3 psia. The

energy for stripping is provided through the use of saturated steam at a pressure of 45 psia or higher. Heating of the amine solution drives off some water, which enters the stripper as steam and helps desorb CO_2 from the rich amine solution. Most of the lean amine solution is pumped to the lean/rich heat exchanger to heat up the amine entering the absorber. A small portion of it is fed to a reclaimer, where heating to a higher temperature and addition of caustic soda facilitates precipitation of any degradation byproducts and heat stable amine salts.

The CO_2 rich vapor stream from the top of the stripper is passed through a reflux condenser where it is partially condensed. The resulting two-phase steam is separated into CO_2 and condensate, which is fed back to the stripper. The CO_2 stream recovered at a pressure of around 25 psia is further dried and compressed to a high pressure required for the sequestration, i.e. at about 1500 psia for injection into the ocean or geological formation.

Chemical absorption with alkanolamines has been generally used in processes such as natural gas sweetening and hydrogen production for the rejection of carbon dioxide [1]. However, the CO_2 partial pressure in these applications is significantly greater than that in flue gas applications. The particular choice of alkanolamine is primarily dictated by the requirements of the specific application.

For many years, MEA was almost exclusively used for removal of CO_2 and H_2S. However, the introduction to newer alkanolamines such as MDEA is in effort to reduce the operating costs and corrosion rates. However, the slower reaction of MDEA with CO_2 was compensated through the addition of small amounts of rate-promoting agents such as DIPA and piperazine In applications such as natural gas treating, industrial practices dictate the use of MDEA with a faster reacting amine. However, this choice will not be effective for CO_2 recovery from flue gas because reaction rate of MDEA with

CO_2 is very slow at low partial pressures leading to absorption columns that are very tall to compensate for the slow reaction rate. This would incur high capital cost to the plant.

The separation of CO_2 from flue gas using chemical absorption with alkanolamines is complicated by these factors; low partial pressure of CO_2 (less than 2psia) and the presence of O_2 in the flue gas. The low CO_2 partial pressure necessitates the use of MEA based systems. However, while MEA may have the advantage of fast reaction rate with CO_2 at low partial pressures as compared to other alkanolamines, there are significant disadvantages such as high heat of reaction, which will cause liberation of high temperature. MEA also has a limited absorption capacity and may cause significant corrosion problems. The presence of O_2 in the flue gas will also cause rapid degradation of alkanolamines. The degradation byproducts lead to corrosion problems and cause significant deterioration the overall separation performance

CHAPTER 3

METHODOLOGY AND PROJECT WORK

3.1 METHODOLOGY OF STUDY

The whole research project encompasses several stages. The initial stage of the project was to conduct literature research from various resources such as books, encyclopedias, journals, previous research articles and online journals via Internet access. This was done to gain background information and some theoretical knowledge on the applications of amine in the gas absorption process. The next stage of the project was the proper planning of the experimental procedure. Since the equipment to be used was also currently utilized by the other undergraduates, proper planning of the modification to the wetted wall gas absorption column was required to ensure the smooth flow of the experiment. The wetted wall gas absorption column was modified accordingly by removing some of the existing piping and changing the configuration of several fixtures of the equipment. The sample probe from Yokogawa IR Gas Analyzer IR 200 was also attached to the existing setup to provide an analytical means to quantify the amount of CO_2 leaving the column.

3.1.1 Experimental method

The experiments for CO_2 absorption in alkanolamines were performed in a wetted wall gas absorption column to study the following parameters:

1. Effect of constant concentration of primary amine (MEA) with varying solvent flow rate on the total moles of CO_2 absorbed.
2. Effect of varying concentration of primary amine (MEA) on the absorption capacity of solvent as well as maximum overall CO_2 removal efficiency.

3. Comparison between performance of single primary amines (MEA) and mixed amines (MEA+DEA) on the total moles of CO_2 absorbed.

3.1.3 Experimental setup

The schematic diagram of the experimental setup for studying the reaction between the amine solvents and carbon dioxide is shown in Figure 1. The equipment required to perform the experiment are the Armfield Wetted Wall Gas Absorption Column and Yokogawa IR Gas Analyzer IR 200. The other apparatus needed are the following; purified CO_2 gas cylinder, pure N_2 gas cylinder, cylinder pressure regulator and mobile temperature sensor. The wetted wall column apparatus is a continuous flow absorber with carbon dioxide and nitrogen continuously fed to the column. The gases are introduced at the bottom of the column while the amine solvent is fed from the top of the tower, thus providing a counter-current contact to the absorption column. The amines were obtained from R&M Chemicals with a minimum purity of 99% and were used without further purification. All solutions were prepared with distilled water. The CO_2 gas and N_2 gas with purity if 99.9% were supplied from commercial cylinders.

The nitrogen is added as a carrier gas to reduce the overall CO_2 vol % so that the IR analyzer can be used in the range of less than 20 vol %CO_2. The CO_2 gas is kept at ambient water conditions by running the CO_2 piping from the cylinder to a simple water bath before entering the column. The gas stream to the wetted wall column was saturated with water at the experiment temperature to avoid heat imbalances in the absorption column. The rotameter is used to control the flow of CO_2 gas into the column. The air rotameter has a working range of 600-5000 mL/min. The CO_2 gas then will flow up the column, counter currently contacting the amine solvent film maintained at the column wall. The exit CO_2 gas is then routed to the IR analyzer probe attached to the column. The concentration of CO_2 can be recorded from the IR analyzer in terms of vol %. The amine from the column is recycled back to the amine reservoir, which has an approximate capacity of 40 litres. The amine solvent circulation in the column is controlled at the water flowmeter panel. The water flowmeter has a range of 20-290 mL/min.

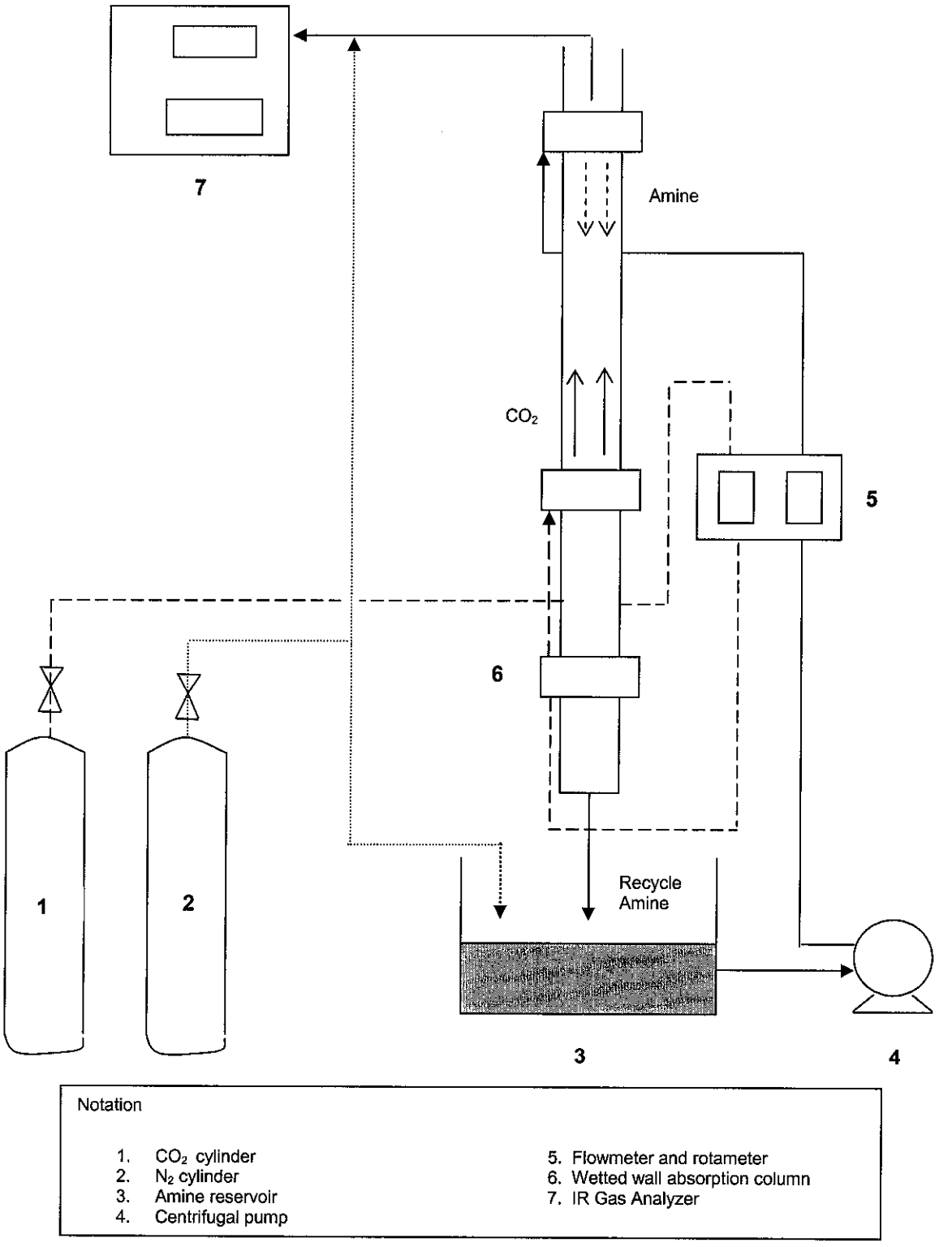


Figure 3.1: Schematic diagram of experimental set up

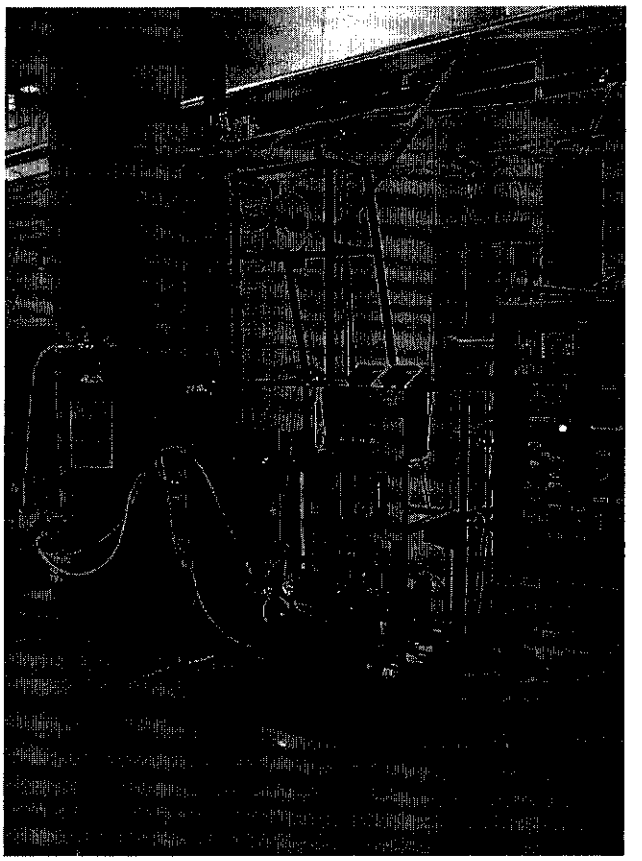


Figure 3.2: Experimental set up of wetted wall gas absorption column for studying absorption of CO_2 in alkanolamines

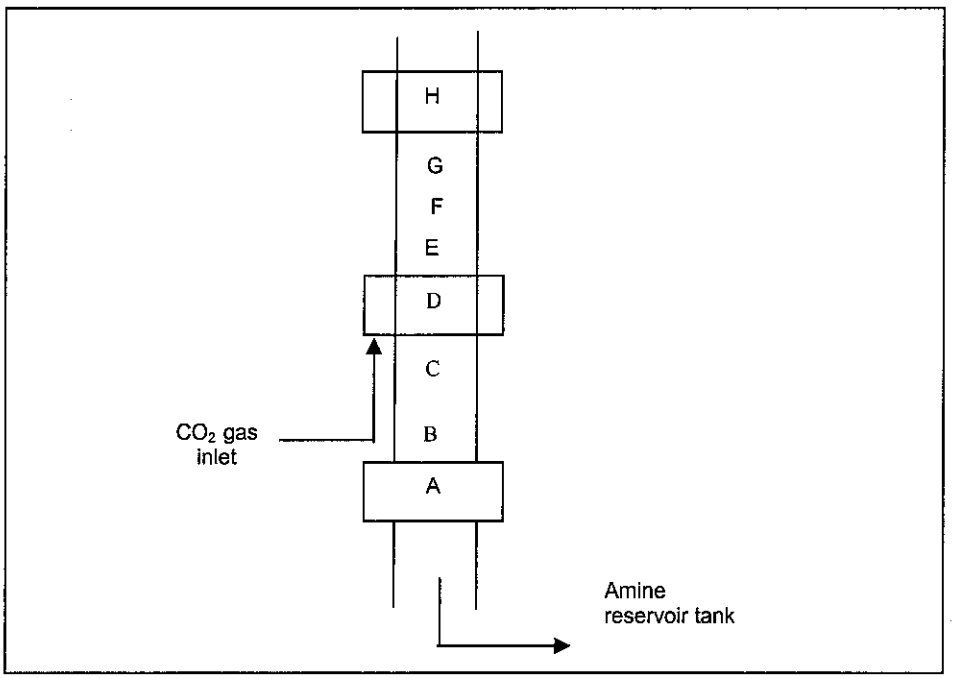


Figure 3.3: Temperature record point along length of wetted wall column

3.2 EXPERIMENTAL PROCEDURE

3.2.1 Preparation of solvent

Stock solutions of MEA were prepared by diluting with distilled water to the required concentration needed in weight % basis. Please refer to the Appendix 1 for sample calculations for preparation of weight % basis amine solutions.

3.2.2 Flowmeter calibration for amine solvent

The flowmeter attached to the Armfield Wetted Wall Gas Absorption Column is for use with water only. Therefore, calibration using amine solvent prior to the absorption is required to ensure the actual amine solvent circulation can be accurately determined. This was done by determining the amount of time taken to fill 100 mL of solvent in a beaker within 1 minute. A run of three readings was recorded to obtain the best average value. The flowmeter was calibrated from the range of 200 ml/min to 280 ml/min. The actual water flowmeter range is between 50 ml/min to 280 ml/min. The observation from the calibration performed shows that the actual flow rate of solvent is less than the measured readings from the display glass of the flowmeter. The actual flow rate of amine is expected to be more viscous as compared to water, this taking a longer time to circulate in the column. The flowmeter calibration curves obtained for the various concentrations of MEA are as obtained as shown in the following figures.

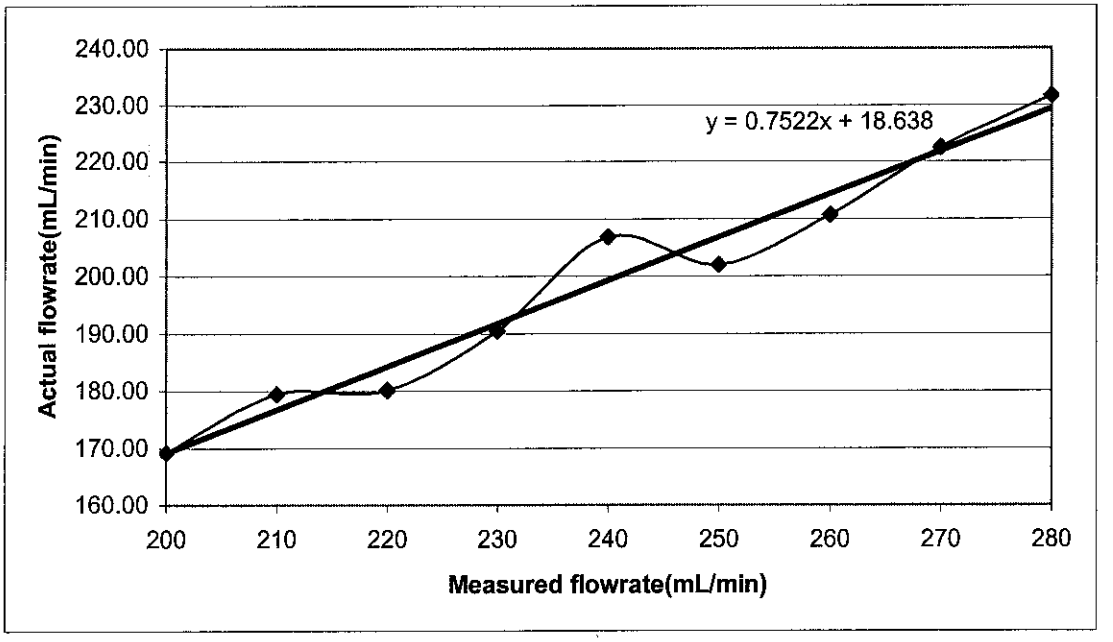


Figure 3.4.1: Graph showing flowmeter calibration curve for solvent 20-wt% MEA

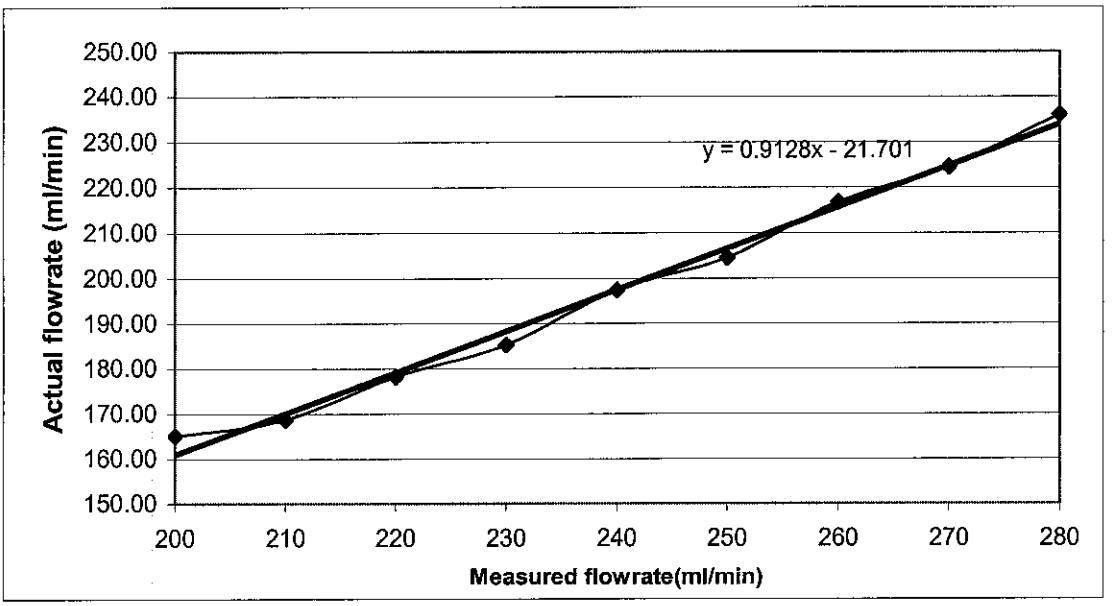


Figure 3.4.2: Graph showing flowmeter calibration curve for solvent 25-wt% MEA

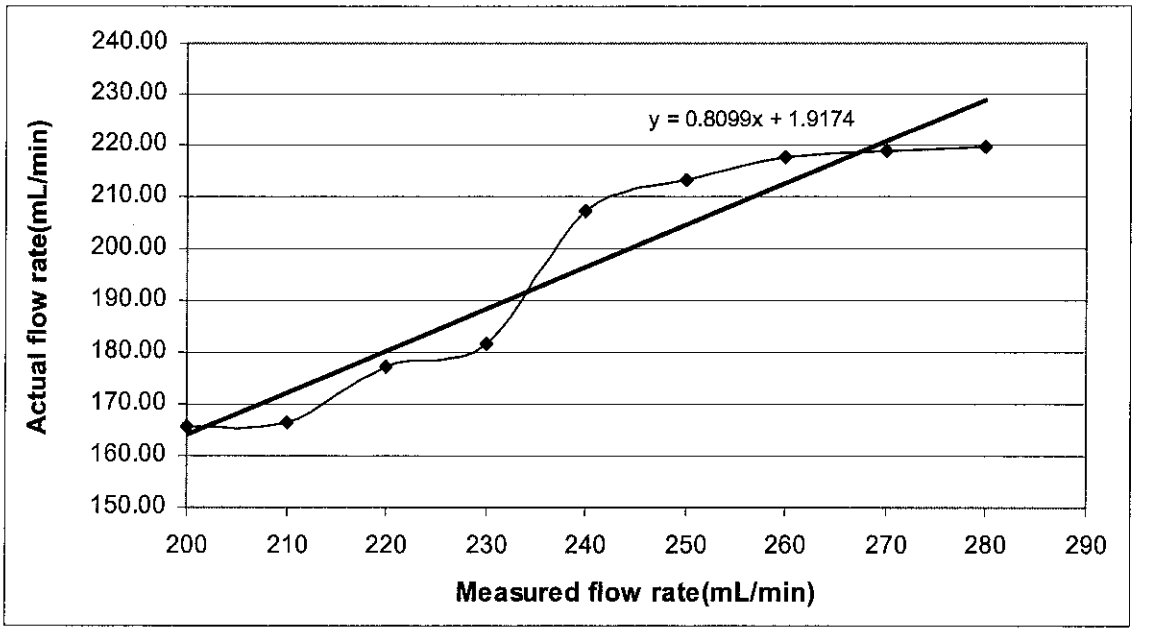


Figure 3.4.3: Graph showing flowmeter calibration curve for solvent 30-wt% MEA

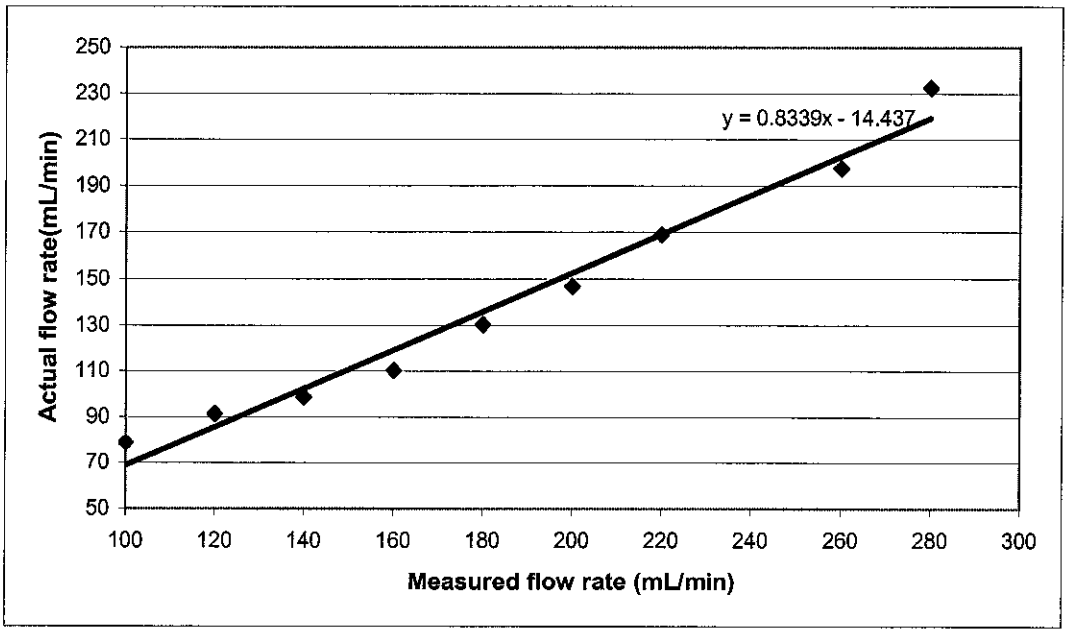


Figure 3.4.4: Graph showing flowmeter calibration curve for solvent 25-wt% DEA and 6.4-wt% MEA

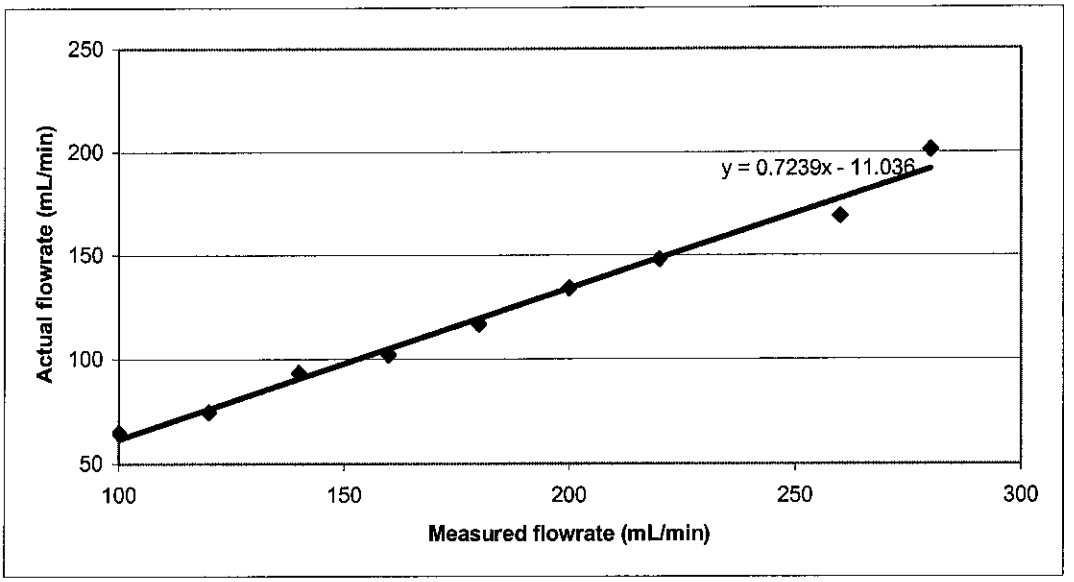


Figure 3.4.5: Graph showing flowmeter calibration curve for solvent 25-wt% DEA and 10.2-wt% MEA

3.2.3 Rotameter calibration for CO_2 gas flow

The rotameter attached to the Armfield Wetted Wall Gas Absorption Column has been calibrated for use with nitrogen. Therefore, a correction factor should be applied to the measured flow displayed on the rotameter to obtain the flow for CO_2 introduced to the column. As obtained from (http://www.omega.com), the corrected flowrate of CO_2 would be as follows.

$$Q_{CO_2} = \frac{\rho_{N_2}}{\rho_{CO_2}} \times \frac{\mu_{N_2}}{\mu_{CO_2}} \times Q_{N2}$$

The correction factor accounts for the different properties of density and viscosity of carbon dioxide as compared to nitrogen. By considering the properties of N_2 and CO_2 at pressure of 101.3kPa and temperature of 20°C, the following equation can be obtained.

$$Q_{CO_2} = 0.62976 \times Q_{N_2}$$

where Q_{CO2} is the actual flow of CO_2 and Q_N is the measured flow from rotameter.

The CO_2 gas flow rate is assumed to be constant for each run of differing solvent flow rate for the same solvent concentration.

Table 3.1: Measured and corrected CO_2 gas flow rate (cm^3/min)

Solvent	Measured gas flow rate (cm^3/min)	Corrected gas flow rate (cm^3/min)
20 wt% MEA	1800	1133.568
25 wt% MEA	2000	1259.52
30 wt% MEA	2200	1385.47
25 wt% MEA+ 10.2% MEA	2410	1517.72
25 wt% MEA+ 6.4% MEA	2350	1479.94

3.2.4 Absorption experiment with CO_2 and amine solvent

The necessary modifications were made to the existing wetted wall gas absorption column before the start of the experiment. This included the connection of the IR gas analyzer probe to the top of the column where the CO_2 gas exits from the column. The prepared amine solution of required weight % concentration is loaded into the amine reservoir tank as shown in Figure 3.1

The flowrate of the amine circulating in the system is adjusted accordingly with the flowmeter. The flowmeter controls the amount of amine withdrawn from the reservoir tank. There were three variations of flow rate performed for each concentration of MEA used (20-wt%, 25-wt% and 30-wt %). The corrected flow rate of solvent was obtained as in Section 3.2.2.

The first run of the experiment was performed for MEA-30wt% solvent with water. Initially, the CO_2 gas is regulated to flow within an allowable pressure limit to the column without starting the amine circulation pump. The CO_2 gas flow rate was maintained at 2200 cm^3/min as displayed on the rotameter. However the actual corrected

gas flow rate is expected to be 1385.47 cm^3/min as discussed in Section 3.2.3. The initial CO_2 vol % at time=0 was recorded from the display panel of the IR Gas Analyzer. After that, the stopwatch is started and the CO_2 vol% value is subsequently recorded from the display panel on a 1-minute interval basis. The temperature along the length of the column was also recorded throughout the duration of the experiment run as shown in Figure 3.3. The experiment is stopped when the CO_2 vol% values remains about the same value over time. This can be considered as the steady state value of CO_2 vol % in the system. Subsequently, the experiment is repeated with differing values of solvent flow rate as done by adjusting the flowmeter accordingly.

The absorption experiment is then repeated for the next MEA solvent concentration. Due to the lack of amine resources, the 30-wt% MEA solvent is diluted by adding distilled water to reach the new concentration of 25-wt% MEA solvent. The next run of 20-wt% MEA solvent is also prepared by diluting the 25-wt% MEA solvent in the amine reservoir tank with distilled water. The assumption is that the amines in the system are not fully loaded with amine so that it can be reused for the next subsequent run.

CHAPTER 4

RESULTS AND DISCUSSSION

4.1 EXPERIMENTAL RESULTS

The experiments performed were for 20, 25 and 30-wt% MEA at three differing solvent flow rates. The absorption experiment was also carried out for two differing mixtures of MEA and DEA with a constant solvent flow rate. The experimental data are shown in Appendix 2-5. The data recorded for each run of the experiment are the entering CO_2 volume % into column, exiting volume CO_2% from the column as well as the temperature along the different lengths of column at a one-minute interval.

The summary of the experiments conducted for this study is as follows.

Table 4.1: Summary of experimental runs performed for this study

No.	Solvent mixture	Solvent flow rate (cm^3/min)		
		Run 1	Run 2	Run 3
1	MEA 30-wt% +H_2O	165.41	177.11	219.67
2	MEA 25-wt% +H_2O	165.12	178.15	236.00
3	MEA 20-wt% +H_2O	169.17	180.13	225.60
4	DEA 25-wt%+ MEA10.2-wt% +H_2O	200.98	-	-
5	DEA 25-wt%+ MEA 6.4-wt% +H_2O	232.35	-	-

The data obtained from the experimental runs are further analyzed and manipulated to obtain more data on the actual moles of CO_2 absorbed and the absorption capacity of the amine solvent.

4.1.2 Determination of moles of CO_2 gas flow absorbed

The raw experimental data collected is initially used to generate plots of the exiting CO_2 vol% from the column as a function of time.

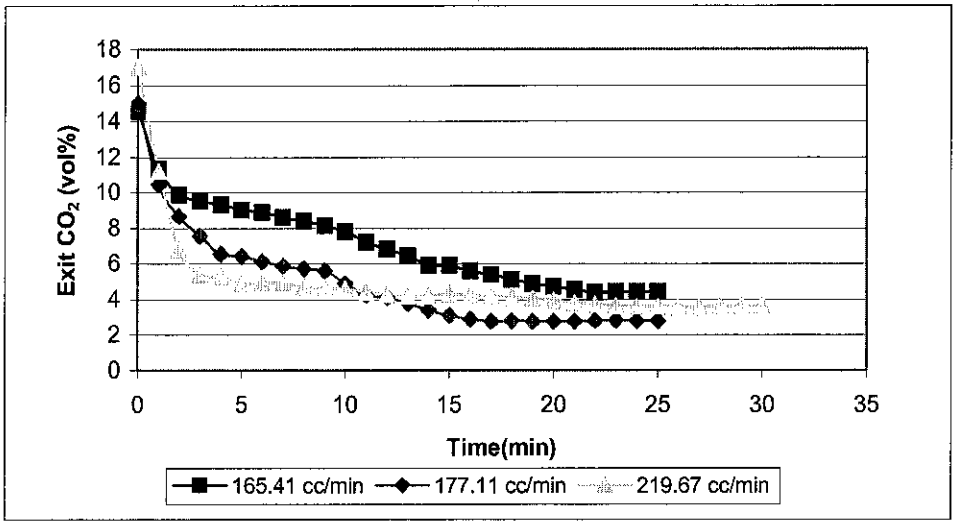


Figure 4.1.1 Graph depicting trend of exit CO_2 vol % from column as function of time for MEA-30wt%

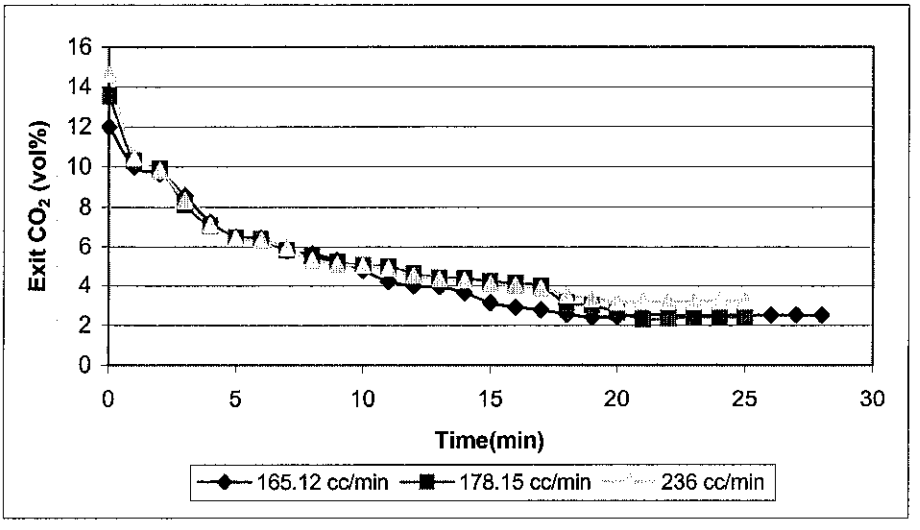


Figure 4.1.2: Graph depicting trend of exit CO_2 vol % from column as function of time for MEA-25wt%

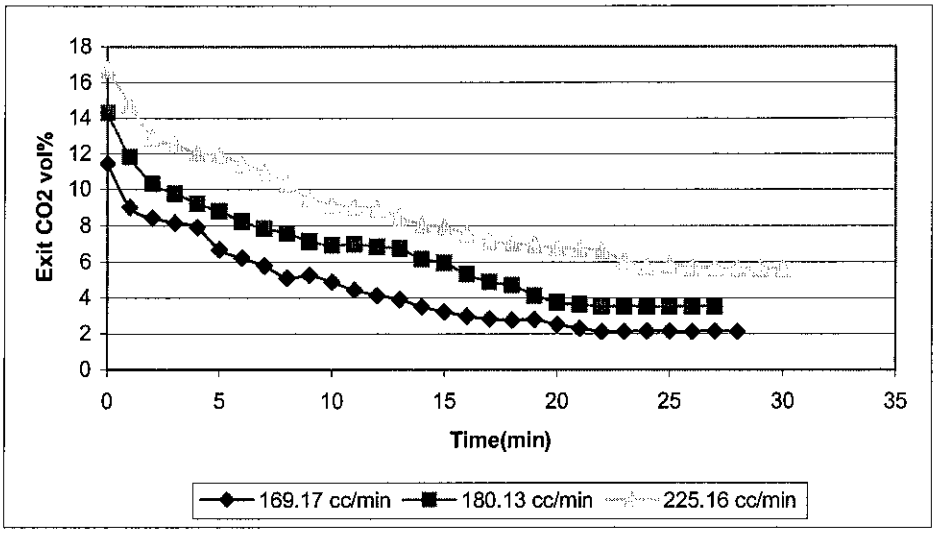


Figure 4.1.3: Graph depicting trend of exit CO_2 vol % from column as function of time for MEA-20wt%

From the figures shown, it can be observed the general trend is of decreasing exiting CO_2 vol% from the column. This corresponds to the absorption process occurring in the column, with amine solvent removing CO_2 from the entering gas. The general trend as observed from the figures is a sharp decline in exiting CO_2 vol% at the initial point of time. The exit CO_2 vol% then tapers off to an almost constant value, which is the point in time when the experiment is stopped. The estimation of the CO_2 flux into or out of the amines can be based on the concentration of CO_2 in the inlet gas and the outlet gas.

However, there is a limitation to observing the actual amount of CO_2 moles entering the column which occurs due to the different values of entering CO_2 vol% into the column at time=0 as seen from the figures above. It was difficult to maintain a constant same value of CO_2 vol% entering the column. This was contributed by the experimental limitations of the non-availability of a mass flow regulator to control the flow of N_2 and CO_2 introduced into column. During the experiment, the ratio of N_2 to CO_2 in the entering gas to the column was controlled manually by regulating the pressure of the gases for both cylinders. This also later contributes to the different flow of gas introduced to the column for each respective run of absorption with varying concentration of amines.

To overcome this limitation and to ease the comparison of data for each solvent flow rate run, the total gas flow rate is calculated by using the following assumption:

Corrected CO_2 gas flow rate (m^3/h) = Q_{CO2}

Mass flow rate of CO_2 gas, m_{CO2} (g/h) = $Q_{CO2}(cm^3/h) \times \rho_{CO2}(g/cm^3)$

Molar flow rate of CO_2 gas, M_{CO2} (mol/h) = $m_{CO2}(g/h) \times (mol/44.01g)$

Therefore it is assumed that the entering CO_2 vol% (in) at time=0 is equals to the initial molar flow rate of CO_2 gas entering the column. Subsequently, the corresponding mol of CO_2 to the next value of CO_2 vol% is found through interpolation assuming linear dependency between moles of CO_2 entering and CO_2 vol % exiting from the column. The CO_2 vol% exiting the column is assumed to be at steady state when the CO_2 vol% values do not fluctuate further. This value is taken as the final CO_2 vol% (out) from the column.

Table 4.2: Summary of total CO_2 (vol %) removed during absorption

Solvent	MEA(20 wt%)			MEA(25 wt%)			MEA(30 wt%)		
	CO_2 vol%			CO_2 vol%			CO_2 vol%		
Measured Flowrate (cm^3/min)	In	Out	Absorbed (In-Out)	In	Out	Absorbed (In-Out)	In	Out	Absorbed (In-Out)
200	11.45	2.11	9.34	12	2.52	9.48	14.55	4.43	10
220	14.33	3.51	10.81	13.55	2.42	11.13	15	2.8	12.2
280	16.73	5.63	11.1	14.67	3.21	11.46	17	3.66	13.34

As seen from the table above, the effect of increasing solvent flow rate and increasing solvent concentration can be observed. As both of these parameters are increased, the effect on the total amount of CO_2 moles absorbed also increases. This will be discussed further in Section 4.2

4.1.3 Determination of amount of mol CO_2 absorbed

To determine the number of moles of CO_2 absorbed, the moles of CO_2 present at each time interval must be calculated using the method as discussed in Section 4.1.2. Thereafter, the difference between the initial mole of CO_2 entering the column and the mole of CO_2 at particular time, t will be the amount of CO_2 absorbed in the amine solvent.

This method to determine the amount of CO_2 absorbed uses the assumption that all entering CO_2 into the column is absorbed into amine with no losses of CO_2 to atmosphere. However, this assumption may prove to be slightly erroneous as there might be release of CO_2 into atmosphere due to leaks or gaps in the installation of piping to the column.

4.1.4 Determination of absorption capacity of amines

The other method to describe the effectiveness of amine in removing CO_2 is the determination of the absorption capacity. The absorption capacity of a solvent in removing CO_2 is given by:

$$\text{Absorption capacity} = \frac{\text{kg } CO_2 \text{ removed}}{\text{kg solvent used}}$$

The mass of solvent used in kilogram was found by multiplying the volume of solvent used and the density for that particular amine.

$$\text{Mass of solvent used (kg)} = \text{Volume of solvent used} \times \text{Density of solvent (kg/m}^3\text{)}$$

4.1.5 Determination of maximum overall CO_2 removal efficiency

The performance of the MEA solvent at differing concentrations can be compared in terms of the maximum overall CO_2 removal efficiency. This is expressed as a percentage of total moles of CO_2 absorbed per initial moles of CO_2 into the system.

$$\text{Maximum } CO_2 \text{ removal efficiency (\%)} = \frac{\text{Initial moles of } CO_2 - \text{Final moles of } CO_2 \text{ absorbed}}{\text{Initial moles of } CO_2}$$

The effect of MEA solvent concentration on the maximum CO_2 removal efficiency is discussed further in Section 4.2.2

4.2 DISCUSSION

4.2.1 Effect of solvent flow rate

The solvent rates were varied from a lower flow rate to intermediate flow rate and a maximum flow rate. The varying of the flow rate of amine solvent was done by controlling the flow at the water flowmeter attached to the gas absorption wetted wall column. However, the flowrate of amine solvent should be corrected as the water flowmeter has been calibrated for use with water. From Table 3.1, the corrected flow rate is less than the flow rate displayed at the flowmeter. The effect of different amine concentrations will also affect the flowmeter readings. A higher amine concentration solvent is expected to flow slower within a given time interval due to its more viscous nature. A more dilute solution of amine solvent would circulate through the absorption system more quickly as compared to a more concentrated amine solvent solution.

For this study, the effect of variation in flow rate is only considered for differing MEA amine concentration. To observe the effect of varying flow rates, an analysis was made based on the data recorded throughout the experiment. From the raw data obtained, several calculations were made in order to obtain the actual moles of CO_2 absorbed during the experiment as well as the absorption capacity of the solvent. This has been discussed in Section 4.1 previously.

As observed from the figures, the general trend is that as solvent flow rate increases in circulation, the moles of CO_2 absorbed per mL of solvent also increase. This is because as more amine is loaded to the column, more solvent is available to remove the CO_2 from the entering gas stream. The higher solvent flow rate would give rise to more amine able to absorb a given amount of CO_2 flowing into the column. Therefore, the pump circulation should be maintained at a high flow rate within safety limits and within range of the flowmeter to enable more amine solvent to be introduced to the column.

An increase in the solvent flow rate led to an increase in the solvent absorption capacity within the solvent flow rate range applied in this experiment. However, there is a limitation to the actual absorption capacity of the solvent. This restriction occurs due to the stoichiometric loading of amines whereby no further increase of solvent flow rate would be able to improve the solvent absorption capacity.

The limitations to the comparison of effect of solvent flow rate in the system are due to the differing solvent concentration and densities of solution prepared. There will be differences in the actual flow rate to the measured flow rate as shown on the air rotameter. Therefore as basis of comparison, the solvent flow rate would assumed to fall under the following categories of; low flow rate, intermediate flow rate and maximum flowrate. For better comparison purposes, the flowmeter should be calibrated to show the actual flowrate of amine solvent during the experiment to ensure that the flowrate can be approximated to be similar for the differing amine concentrations.

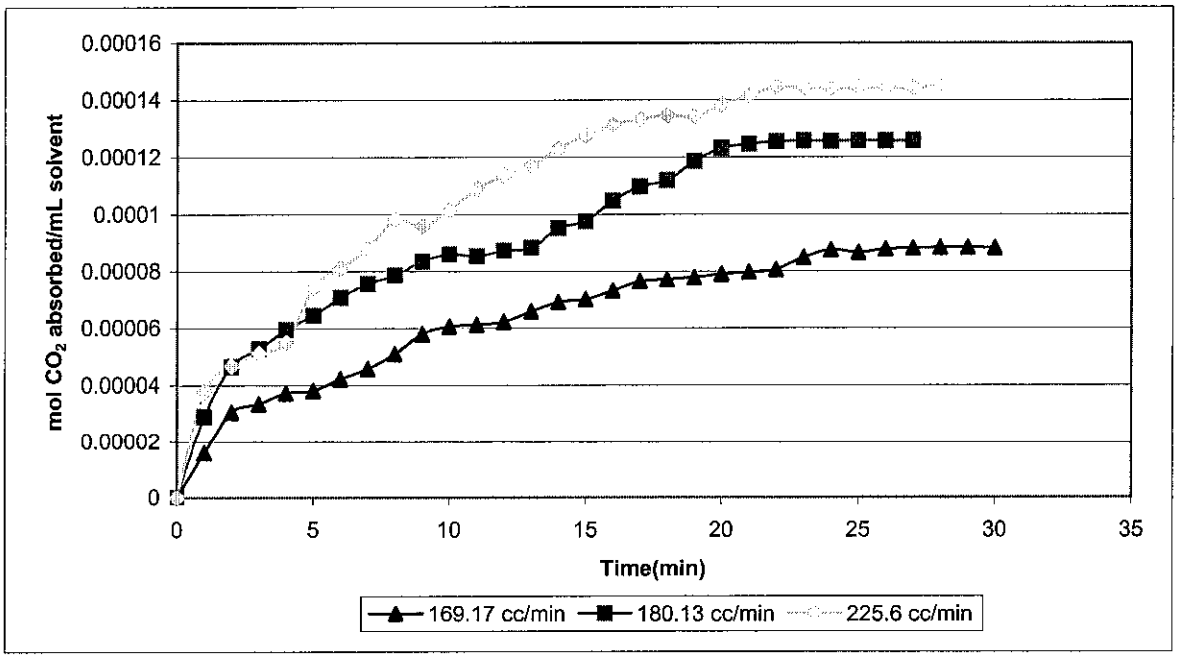


Figure 4.2.1: Graph depicting effect of solvent flow rate for MEA-20wt% solvent

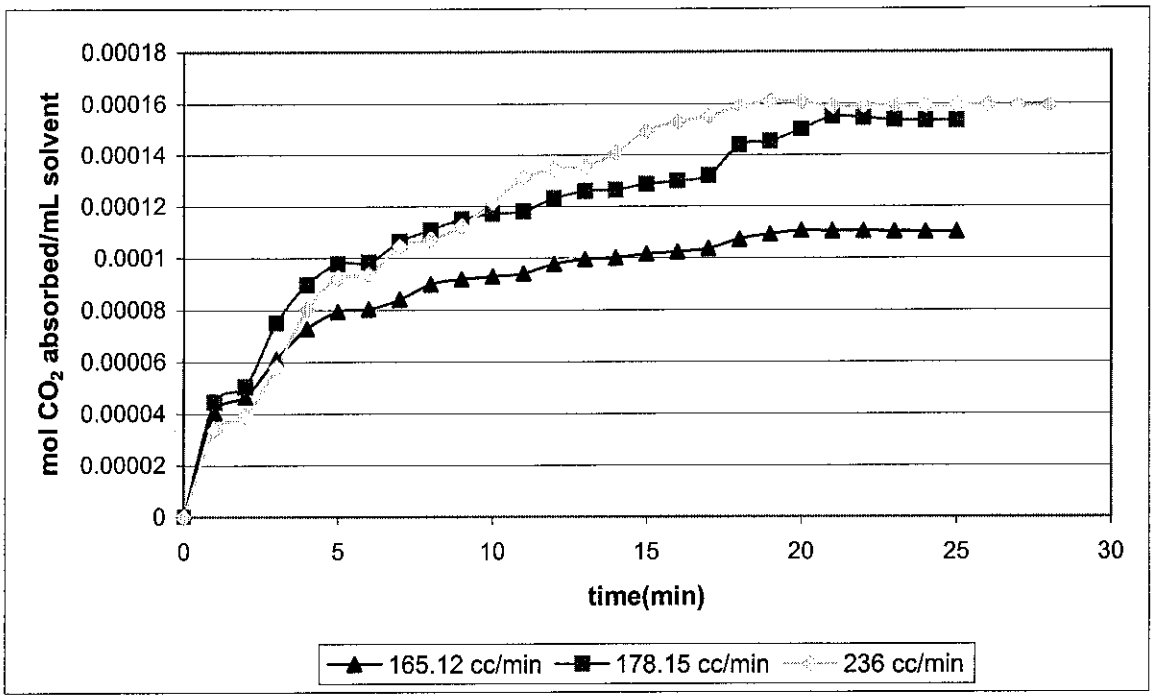


Figure 4.2.2: Graph depicting effect of solvent flow rate for MEA-25wt% solvent

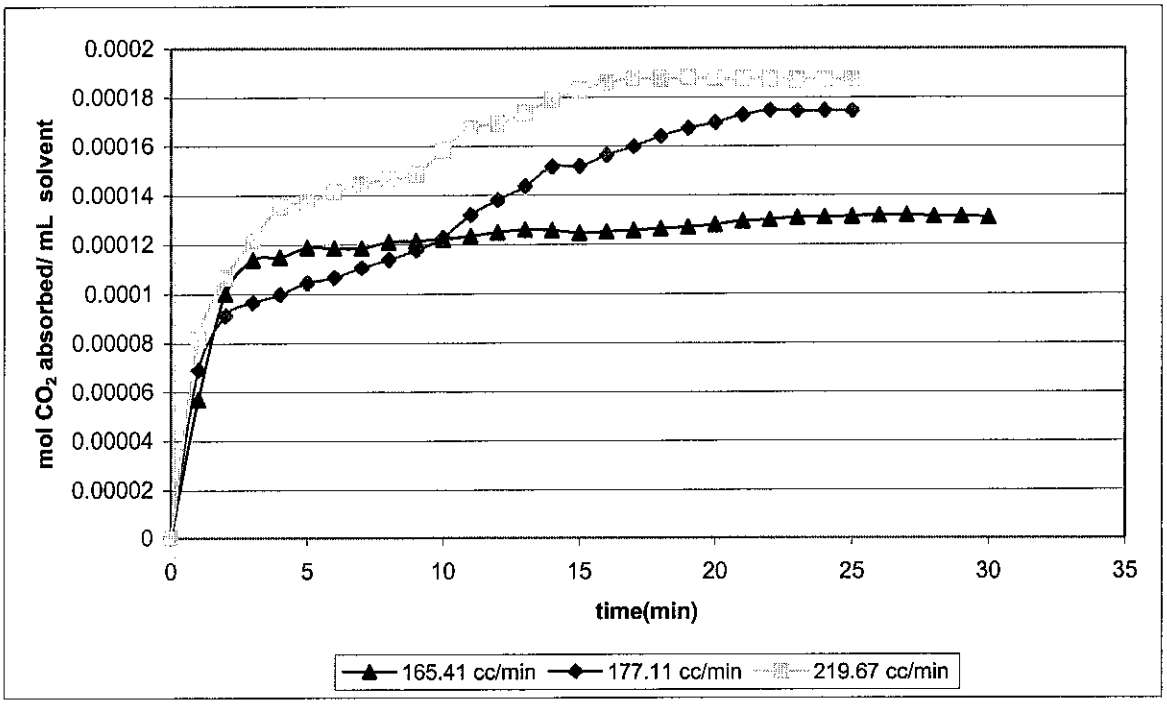


Figure 4.2.3: Graph depicting effect of solvent flow rate for MEA-30wt% solvent

4.2.2 Effect of solvent concentration

In theory, a higher concentration of amine solvent would give rise to better absorption of CO_2 for the given solvent. The variations done for the primary amine concentration was 20-wt% MEA, 25-wt % MEA and 30-wt % MEA. In order to compare the performance of the two solvents, the maximum CO_2 removal efficiency was calculated for each concentration of MEA solvent used.

The maximum CO_2 removal efficiency was calculated as follows:

Maximum CO_2 removal efficiency (%)

$$= \frac{\text{Initial moles of } CO_2 - \text{Final moles of } CO_2 \text{ absorbed}}{\text{Initial moles of } CO_2} \times 100\%$$

From work previously done by Yeh A.C., Bai H., 1999, it was reported that with MEA solvent concentrations of greater than 28 wt% would not yield any improvement in CO_2 removal efficiency. This is because the CO_2 removal efficiency at 28% has been reported to be quite high, at a value of 92%.

The overall maximum CO_2 removal efficiency for this experiment was obtained at 21% using MEA solvent concentration of 30-wt%. This low value could be contributed due to the limitations in the experiment whereby the amines could not be regenerated before use with the subsequent absorption run. Therefore, the CO_2 remains loaded in the amine solution. As a result, the amine is unable to absorb more CO_2. The other contribution to the decreased maximum CO2 removal efficiency is the loss of CO_2 to the atmosphere as the system is not under tight experimental control.

However, there is a limitation to the concentration of MEA used, as MEA is highly corrosive in nature. Further experiments should be conducted to determine the solvent threshold concentration value to which the solvent absorption capacity would not increase further.

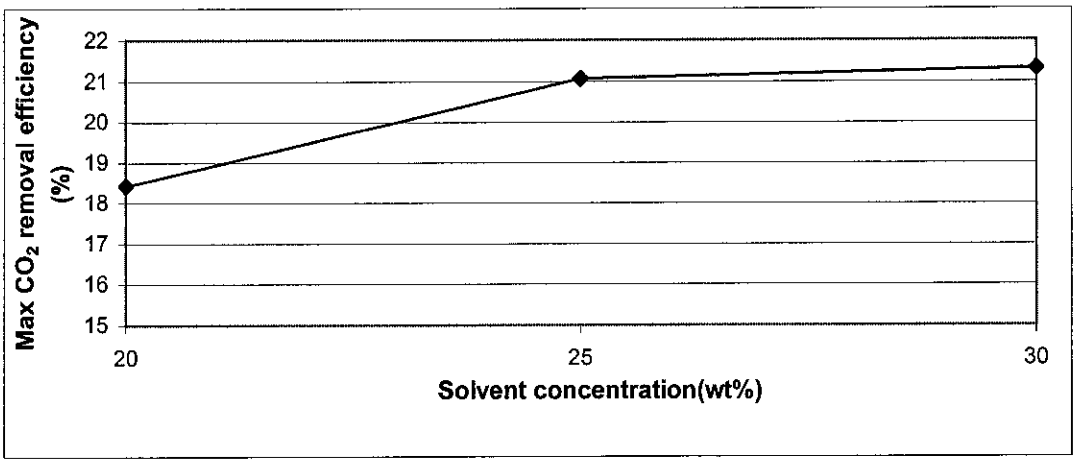


Figure 4.4.1: Graph showing effect of MEA solvent concentration maximum CO_2 removal efficiency

The solvent absorption capacity obtained for this experiment is found to be close to the absorption capacity values reported by Yeh A.C., Bai H., 1999. The previous work cited that the CO_2 absorption capacity of MEA solvent is almost not affected by the solvent concentration. The values reported were approximately 0.38-0.36 kg CO_2/ kg MEA for MEA solvent concentrations range from 7% to 35-wt%.

Based on the results obtained in this experiment, the absorption capacity of the MEA solvent decreases with increasing solvent concentration. The values obtained are 0.29, 0.23 and 0.20 kg CO_2/kg MEA for MEA concentration of 20%, 25% and 30-wt% respectively. These figures correspond to the highest flow rate of solvent used in the individual experimental run. The decrease in absorption capacity can be explained by the following analysis considering the weight of solvent and total CO_2 removed during absorption.

Theoretically, as solvent concentration increases, the total CO_2 removed from the gas stream should also increase. However, for this experiment, the total CO_2 removed at higher concentration of MEA solvent was not much higher than at lower concentration. There was only a marginal improvement reported. Therefore, the main factor influencing the absorption capacity of the solvent would be weight of solvent. Therefore a lower

concentration of solvent used would lead to a larger ratio of kg CO_2 removed per kg of solvent and thus a higher absorption capacity.

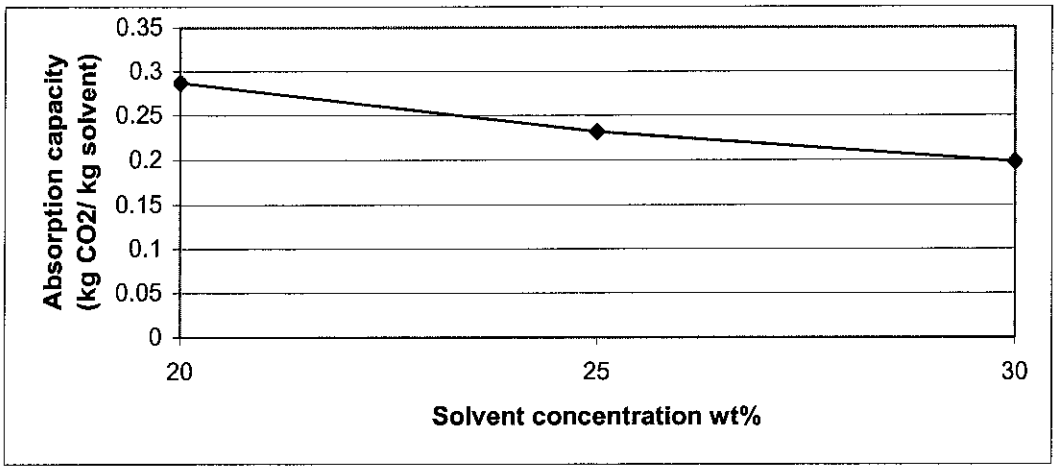


Figure 4.4.2: Graph showing effect of MEA solvent concentration on solvent absorption capacity

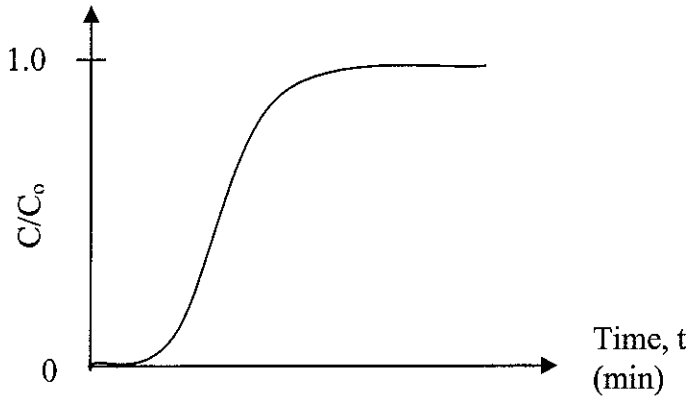


Figure 4.3: Theoretical breakthrough curve for CO_2 absorption with amines.

The theoretical breakthrough curve can be obtained by plotting the ratio of CO_2 concentration of the gas mixture exiting the column, C to the initial CO_2 inlet concentration, C_o versus time. The point at which the CO_2 outlet concentration equals to the inlet concentration is the breakthrough point for the CO_2 absorption process. However, there is insufficient data for this experiment to obtain the breakthrough curve as the experiment was stopped before the breakthrough point reached. The breakthrough point occurs when the amines are no longer able to absorb CO_2 and is considered to be fully loaded with CO_2.

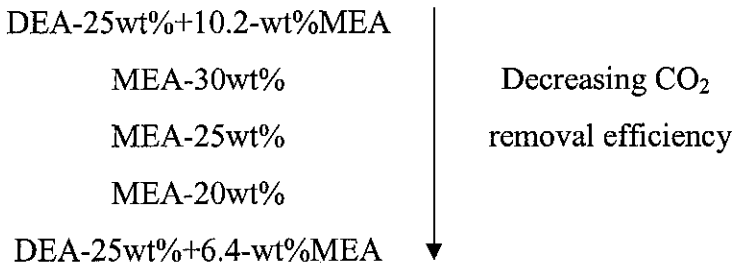
4.2.3 Effect of single amines and mixture of amines

Theoretically, the mixture of primary and secondary amines will give better performance to remove CO_2 as compared to sole single primary amine. However, the optimum mix of amines is crucial to ensure the benefits of the primary and secondary amine can be maximized to produce a solvent far superior in removing CO_2 from natural gas.

From the results obtained as shown in Figure 4.3.1, the mixture of DEA-25wt% and MEA-10.2wt% gave the highest moles of CO_2 absorbed per mL of solvent. However, the next mixture of DEA-25wt% and MEA-6.4 wt% did not yield a good result as compared to MEA-30wt%. This mix has been determined not to be the optimum mix for CO_2 effective removal. The possible explanation is that the MEA concentration in the amine mixture solvent contributes to the main removal factor of CO_2 from the gas stream. Thus, the decrease in the MEA concentration in the give mixture reduces the efficiency of the solvent in removing CO_2.

The lowest amount of CO_2 moles absorbed per mL of solvent was obtained from the run with DEA-25wt%+6.4-wt%MEA. This corresponds to the explanation discussed earlier where MEA is considered the active removal agent in the mixture of primary and secondary amines used. In comparison, the total moles of CO_2 removed with MEA-20wt% are still higher than the total moles of CO_2 removed for the DEA-25wt%+6.4-wt%MEA. This indicates that the concentration of MEA is too low in this mixture, thus a fast absorption rate normally present for MEA could not be achieved. Another interesting observation is that by diluting the MEA concentration in the amine mixture from 10.2-wt% to 6.4-wt%, the effect on the total moles of CO_2 absorbed per mL of solvent decreases almost by two-fold from 0.00016 to 0.00008. This further confirms that MEA concentration in a mixed amine solvent is the major factor in determining the effective removal of CO_2.

The performance of the solvents in decreasing order can be grouped as follows:



A primary advantage of use with MEA is that the active group in MEA reacts faster as compared to other secondary amines. This can be observed in the Figure 4.1.1, 4.1.2 and 4.1.3 shown earlier depicting the exiting CO_2 vol % versus time. From the figures shown, it is observed that the exiting CO_2 vol% reaches 50% CO_2 inlet concentration within the first 10 minutes of the absorption run. As compared to other secondary amines (DEA) or tertiary amines (MDEA), MEA still primarily acts faster to remove CO_2. Primary amine MEA has been shown to have a higher rate of absorption as compared to secondary amines such as DEA However, the main issue with use of MEA is its highly corrosive nature, which can affect downstream equipment in a natural gas processing plant. Its other disadvantages are its low loadings and high regeneration cost. Therefore a blend of primary and tertiary amine would be a better choice as a solvent. The main advantages of tertiary amines are its high loadings and low corrosive nature. Tertiary amines also have lower heat of reactions, thus can be recovered at the stripper side with lower regeneration energy cost.

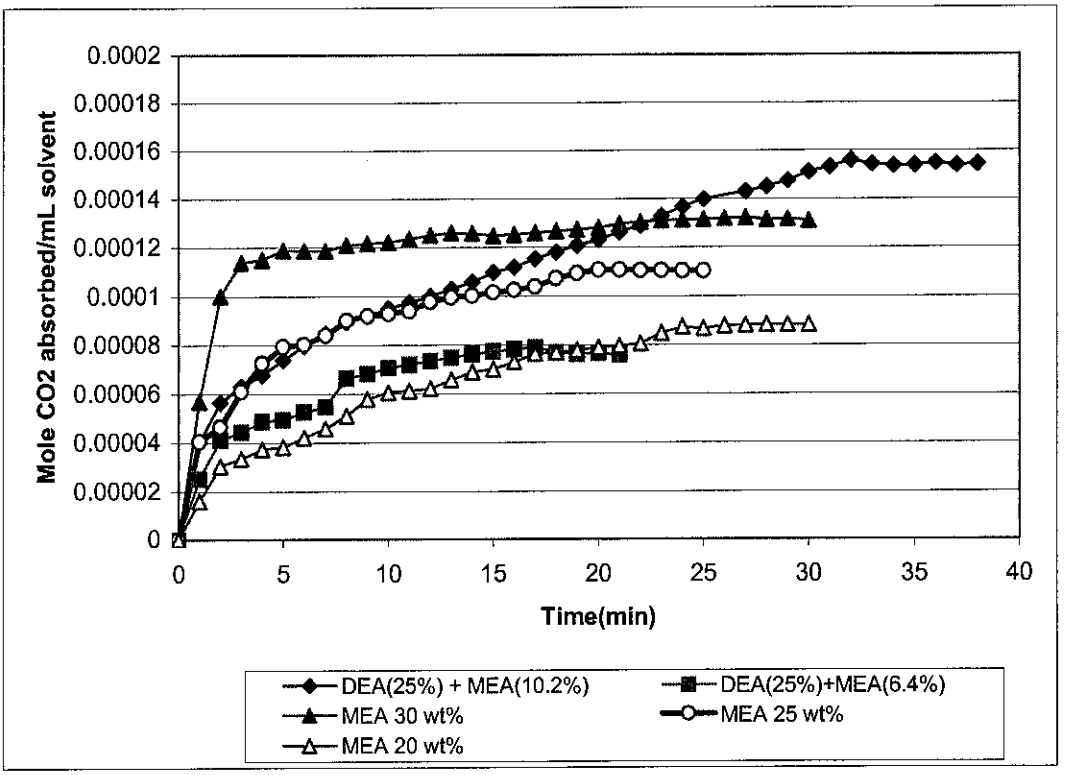


Figure 4.5: Graph depicting effect of varying mixture of solvents on the total moles of CO_2 absorbed per mL of solvent.

4.2.4 Effect of reaction temperature

Although the operating temperature was kept constant, temperature variations in the wetted wall column were unavoidable due to exothermic reaction between CO_2 and the amines. The temperature variation of MEA scrubbing gradually increased to the maximum temperature of 29°C and then gradually decreases until the CO_2 vol % exiting the column remains about constant. There was very little temperature difference in the reaction temperature noted for same concentration of MEA with varying flowrates. Yeh A.C., Bai H., (1999) reported that the maximum temperatures using the MEA solvent increase with increasing the solvent concentration. It was reported that the maximum temperature using 35-wt% MEA solvent is approximately 50°C.

The effect of increasing solvent concentration on reaction temperature was not significant and therefore the results were not shown in this study. Although solvent concentration

was increased, the limitation imposed that the amines recycle was deployed for this experiment. Therefore the expected temperature changes could have been affected by the CO_2 loading of the amines.

However the major difference in reaction temperature occurs when comparing the single amine solvent of MEA-30wt% and mixed amine solvent of DEA-25wt% and MEA-10.2wt%. The maximum reaction temperature for the run with mixed amine solvent of DEA-25wt% and MEA-10.2wt% was recorded to be at 30.4°C as compared to the MEA-30wt% maximum reaction temperature of 26.2°C. For this study, a new batch of solvent was prepared in the amine reservoir for this mixed amine system. Therefore, the performance of this amine mixture of DEA-25wt% and MEA-10.2wt% would be considered to be better than the dilute single amine solvent.

The plot of the reaction temperature at point E of the column as a function of time is as shown in Figure 4.6. The general trend as observed is that the mixed amine system has a higher reaction temperature as compared to the single amine system. The high temperature indicates that the heat released in the scrubbing process when using the mixed DEA+ MEA solvent would require more heat during regeneration.

The sharp increase in the temperature of the wall indicates that the amine and CO_2 reacts in an exothermal manner. After the sharp incline, the temperature remains to about constant with slight fluctuations that could be contributed by the ambient effect on the temperature of the column wall.

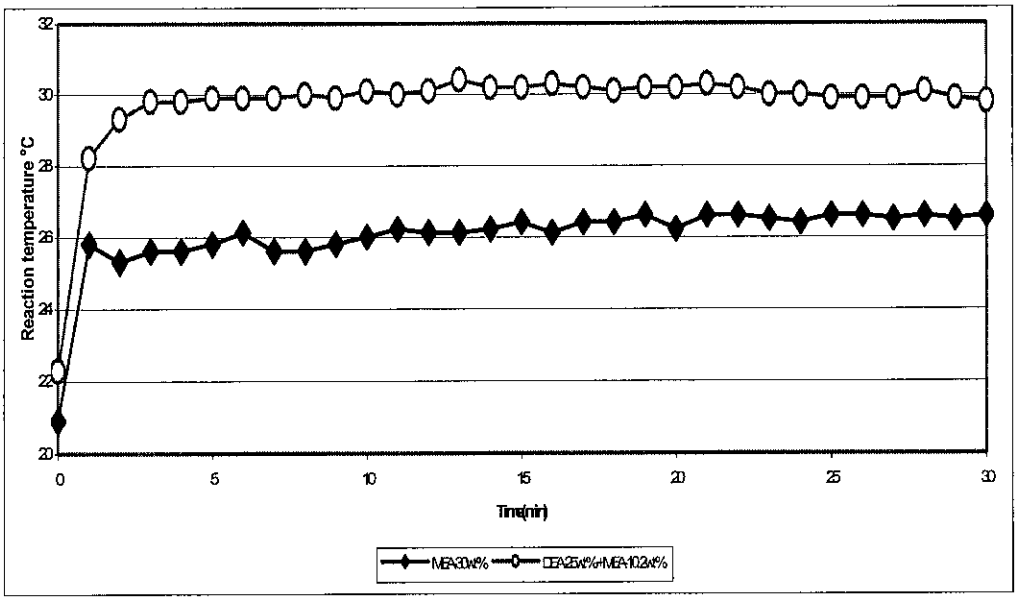


Figure 4.6: Graph showing comparison effect of single MEA solvent and amine mixture solvent on reaction temperature

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Alkanolamines have long been regarded as effective chemical absorbents in removing CO_2 from natural gas as part of the gas sweetening process. There is also growing interest in applications of alkanolamines in removing CO_2 from flue gas to reduce CO_2 gas emissions. Potential recovery of CO_2 can be further used for CO_2 sequestration.

The study on absorption of CO_2 with amines was performed with varying effect of amine concentration; solvent flow rate and mixtures of amines. Overall, the objectives for this project have been successfully fulfilled.

From the absorption experiment conducted, the reaction between CO_2 and amines is determined to be an exothermic reaction. This is indicated by the increase of temperature along the column.

The results from the experiment showed that for increasing amine concentration of MEA from 20-wt% to 30-wt%, the overall absorption capacity of the solvent decreases. The maximum CO_2 removal efficiency is found to be increasing with increasing MEA concentration.

For the comparison of different solvent mixtures, the DEA-25wt%+MEA-10.2wt% showed the best performance in terms of maximum CO_2 removal efficiency. The MEA-20wt% showed the poorest performance in this area. The higher reaction temperature recorded during absorption process for the solvent DEA-25wt%+MEA-10.2wt% indicates a higher heat requirement during regeneration.

From this study, the main factor which drives the CO_2 absorption process in a mixed amine system is the concentration of MEA in the mixture. A decrease in MEA concentration would lead to a decrease in the total moles of CO_2 removed.

5.2 RECOMMENDATIONS

The recommendations to be made are based on several aspects to further improve the current research. Furthermore, this study is considered to be a first in Universiti Teknologi PETRONAS. There is much room to conduct further research for the study of alkanolamines and CO_2.

The suggested parameters of study are the effect of mixtures of solvent i.e. sterically hindered amines such as AMP and primary amines such as MEA. This can potentially explore the benefits of reaping the best individual properties of amines to be combined into an effective absorbent for CO_2 removal. Due to limitation of time and availability of amines, the performance of only two mixtures of MEA and DEA can be reported in this study. It is recommended that further experiments should be done to discover the optimum percentage of a mixed primary and secondary amine

There are also several improvements that can be made to the experimental setup. Since the reaction of CO_2 and amine is an exothermic one, it would liberate heat during the absorption process. As stated in previous work by Yoon J.H et. al (2001), the absorption column should be mounted in an air bath to keep the temperature constant within $\pm$ 0.1°C. This will lead to fewer fluctuations in the temperature as absorption process mostly favors a decreased temperature condition. The air bath should consist either of a heater or refrigerator to control the temperature. With the temperature air bath, the effect of operating temperature on the CO_2 absorption process with amines can be further studied.

The reaction kinetics between CO_2 and amines are highly complex and dependent on parameters such as amine type, solvent concentration, partial pressure of CO_2 and temperature. Therefore, simulation modeling would be required to correlate the

thermodynamic and solubility data of CO_2 in alkanolamines. Further study is recommended in this area to enhance understanding of the actual reaction mechanism between the active alkanolamine group and CO_2.

Most of the previous investigations performed for CO_2 absorption system were done by simple reactor vessel or wetted wall column. For further research purpose, the gas absorption can be performed in a packed column.

Suggested future work for this experiment is to quantify the absorption rate of CO_2 in amines by performing experiments to determine the liquid film mass transfer coefficient, k_L.

The current study performed did not consider the regeneration of amine solvent. After a sufficiently long period of CO_2 absorption, the amine solution would become saturated and regeneration of the exhausted amine would be required to recover the solvent. It is recommended for future experimental purpose that this regeneration step be included in the experimental procedure. Furthermore, a preliminary investigation can be made to compare the regeneration efficiencies between the different solvents used. This is done by comparing the total CO_2 absorption capacity and maximum CO_2 removal efficiency prior and after to the regeneration of the solvent.

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APPENDIX 1: Calculation for preparation of amine solvent solutions in wt % basis

Table 1a: Densities of MEA and DEA

Type of amine	Density (kg/m^3)
DEA	1090
MEA	1020

$$\text{Weight percentage \%} = \frac{\text{A kg solute}}{\text{B kg solution}}$$

Assume for preparation for 30-wt% MEA in water

$$30\% = \frac{Y\ (m^3) \times \rho_{MEA}(kg/m^3)}{[Y\ (m^3) \times \rho_{MEA}(kg/m^3)] + Z(m^3) \times \rho_{H20}(kg/m^3)}$$

where Y = volume of MEA required

Z = volume of H_2O to dilute solvent = 15 L = 0.015 m^3

ρ_{H20} = 1000 kg/m^3

Therefore,

$$[1020\ kg/m^3 \times Y\ (m^3) + 0.015 m^3(1000\ kg/m^3)] \times 0.3 = 1020\ kg/m^3\ Y(m^3)$$

$$Y = 0.00630\ m^3$$

$$= 6.3\ L \text{ of MEA required}$$

Appendix 2: Experimental Data for effect of varying solvent flow rate with MEA-30wt%

Table 2a: Data recorded for flowrate =165.41cm^3/min

			Temperature °C								
t/min	CO_2 (vol%)	Inlet T	A	B	C	D	E	F	G	H	Tank
0	14.55	23.8	23.1	23	22.9	22.7	23.2	23.5	23.6	23.3	24.2
1	11.34	23.1	23.1	24	23.9	21.6	24.6	24.6	24.5	23.2	23.9
2	9.89	23.1	23	24.5	24.4	21.8	25.1	24.6	24.3	23.7	23.6
3	9.54	22.9	23.1	24.7	24.7	21.6	25.1	24.8	24.7	23.9	23.8
4	9.32	23.1	23	24.6	24.4	21.2	25.1	25.1	24.6	23.8	23.7
5	9.02	23.1	23	24.3	24.3	21.1	25.3	25	24.9	24	23.9
6	8.88	23.1	23.2	24.6	24.5	20.5	25.1	25.1	24.8	24.1	23.8
7	8.62	23.1	23.1	24.8	24.4	20.8	25.3	25.2	24.9	24.1	23.6
8	8.41	22.8	23.1	24.9	24.6	20.8	25.4	25.4	25	24.3	23.6
9	8.16	23	23.1	25	24.7	20.2	25.6	25.4	25	24.5	23.9
10	7.82	22.8	23.1	24.9	24.9	20.2	25.4	25.3	25.3	24.6	23.1
11	7.21	22.8	22.8	24.8	24.8	19.9	25.6	25.3	25.3	24.6	23.9
12	6.82	22.8	22.8	24.8	24.8	19.7	25.6	25.5	25.2	24.6	24.1
13	6.45	23.1	22.8	25	25.1	20.2	25.8	25.8	25.4	24.9	23.8
14	5.93	22.9	23.1	24.7	24.7	20.1	25.8	25.3	25.4	24.8	24.2
15	5.91	22.9	22.9	24.8	24.8	20.1	25.9	25.5	25.4	24.8	24
16	5.62	22.2	22.2	24.9	24.9	19.9	25.9	25.6	25.5	24.9	24.3
17	5.39	22.3	22.3	24.6	24.6	19.8	25.7	25.6	25.5	25	24.1
18	5.11	22.8	22.8	24.7	24.7	19.7	25.9	25.6	25.3	25	24.1
19	4.89	22.9	22.7	24.7	24.6	19.9	26	25.5	25.4	25.1	24.2
20	4.74	22.9	22.8	24.8	24.7	20	26.1	25.5	25.4	25.1	24.3
21	4.54	23.3	24.6	26.3	26.3	23.8	26.6	26.6	26.5	25.6	25.1

22	4.41	23.3	24.7	26.1	26.4	23	26.5	26.4	26.1	25.8	25.5
23	4.43	23.1	24.5	26.4	26.4	23.3	26.6	26.5	26.4	25.9	25.2
24	4.42	23.4	24.6	26.4	26.3	24.4	26.5	26.5	26.5	25.8	25.1
25	4.43	23.4	24.6	26.4	26.3	24.1	26.6	26.5	26.4	25.8	25.2

Table 2b: Data recorded for flowrate =177.11 cm^3/min

		Temperature °C									
t/min	CO_2 (vol %)	Inlet T	A	B	C	D	E	F	G	H	Tank
0	15	23.8	24.4	25.4	24.9	24.6	25.7	25.5	25.7	25.7	23.9
1	10.45	23.1	24.5	25.3	24.8	24.7	26.9	25.7	25.7	25.6	23.8
2	8.64	23.1	24.5	25.3	24.8	25.4	26.7	26	25.7	25.6	23.6
3	7.56	22.9	24.4	25.6	25	25.4	27	26.1	25.8	25.6	23.6
4	6.55	23.1	24.8	25.7	24.7	25.8	27	26.3	25.9	25.8	23.9
5	6.42	23.1	24.6	25.6	24.8	26	27.1	26.4	26.1	25.9	23.1
6	6.12	23.1	23.6	25.5	24.9	25.6	27.2	26.6	26.1	25.8	23.9
7	5.89	23.1	23.7	25.7	24.6	25.6	27.4	26.5	26.3	25.8	23.5
8	5.74	22.8	24.3	25.8	24.7	25.8	27.3	26.7	26.4	25.9	23.9
9	5.61	23	24.7	25.9	25.4	25.9	27.3	26.8	26.5	26	23.9
10	4.9	22.8	24.3	25.7	25.4	25.8	27.5	26.9	26.7	25.8	23.7
11	4.23	22.8	24.7	25.9	25.8	25.8	27.7	27	26.8	25.7	23.9
12	4.11	22.8	24.8	25.8	26	25.9	27.8	27.1	26.9	25.6	24.1
13	3.78	23.1	24.8	25.8	25.6	26	27.9	27.3	26.9	25.5	24.3
14	3.4	23	24.9	25.9	25.6	25.8	28	27.4	27	25.7	24.2
15	3.11	23.1	25	26	25	25.7	28.3	27.5	27.1	25.6	24.1
16	2.89	23.4	24.5	26.1	25.9	25.6	28.5	27.8	27.2	25.8	24.2
17	2.76	23.1	24.8	25.9	26	25.5	28.5	27.7	27.2	25.7	24

18	2.78	23.3	24.9	25.8	26	25.7	28.6	27.7	27.3	25.7	24.1
19	2.75	23.2	24.7	25.8	26	25.6	28	27.9	27.4	25.6	24.2
20	2.76	23.3	24.6	25.9	26.1	25.8	28.2	27.8	27.4	25.6	24.3
21	2.77	23.1	24.5	25.7	26.2	25.7	28.3	27.7	27.2	25.8	24.1
22	2.78	23.4	24.6	25.6	26.3	25.7	28.1	27.6	27.2	25.7	24.3
23	2.81	23.1	24.7	25.4	26.1	25.8	28	27.5	27.3	25.7	24.1
24	2.8	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2
25	2.8	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3

Table 2c: Data recorded for flowrate =219.67cm^3/min

			Temperature/°C								
t/min	CO_2 (vol%)	Inlet T	A	B	C	D	E	F	G	H	Tank
0	17	23.1	21.8	19.3	20.1	20.1	20.9	21.3	21.4	23.9	23.5
1	11.2	22.9	22.6	27	26.1	22.5	25.8	25.1	24.6	24.1	23.9
2	6.8	22.7	23	25.7	25.6	22.6	25.3	25.1	24.6	24.1	23.9
3	5.4	22.6	23.3	25.8	25.4	23.6	25.6	25.1	24.8	24.2	23.7
4	5.3	22.9	23.6	25.9	25.4	23.6	25.6	25.1	24.8	24.2	23.9
5	4.9	22	23	25.9	25.8	23	25.8	25.6	25.1	24.6	24.1
6	4.93	22.8	24.4	26.8	26	23.9	26.1	25.7	25.3	24.7	24.3
7	4.92	22.9	24.5	25.9	25.6	23.6	25.6	25.6	25.3	24.8	24.1
8	4.68	22.8	24.5	26.1	25.6	24.3	25.6	25.6	25.2	24.7	24.4
9	4.62	23.1	24.4	25.8	25	23.1	25.8	25.4	25.4	24.8	24.4
10	4.57	23.1	24.8	26.2	25.9	24.4	26	25.9	25.6	24.9	24.4
11	4.43	22.6	24.6	26.3	26	23.3	26.2	26.1	25.8	25.2	24.4
12	4.28	23.2	23.6	26.1	26	23.8	26.1	26.1	25.7	25.3	25
13	4.17	23	23.7	26.3	26.2	24.4	26.1	26	25.7	25.2	25.1
14	4.2	23.1	24.3	26.1	25.8	24.3	26.2	25.8	25.7	25.2	24.9

15	4.3	23.1	24.7	26.3	26.2	23.9	26.4	26.1	25.8	25.3	25
16	4.25	23.5	24.3	26.1	26	23.7	26.1	26.2	25.9	25.3	25.2
17	4.19	23.3	24.7	26.4	26.2	23.6	26.4	26.1	26.1	25.4	25.3
18	4.12	22.9	24.6	26.4	26.2	23.6	26.4	26.1	26.1	25.4	25.3
19	4.05	23	24.8	26	25.9	26	26.6	26.4	26.3	25.6	25.1
20	3.96	23.1	24.8	26.1	26.1	23.9	26.2	26.2	26.1	25.3	24.9
21	3.81	23.4	24.6	26.4	26.4	23.8	26.6	26.4	26.1	25.6	25
22	3.75	23.1	24.5	26.4	26.4	23.1	26.6	26.6	26.4	25.6	25
23	3.66	23.3	24.8	26.4	26.1	23.6	26.5	26.3	26.3	25.7	25.3
24	3.64	23.1	24.8	26.3	26.2	23.6	26.4	26.4	26.4	25.6	25.1
25	3.62	23.3	24.7	26.4	26.3	23.6	26.6	26.6	26.3	25.6	25.1
26	3.57	23.3	24.6	26.3	26.3	23.8	26.6	26.6	26.5	25.6	25.1
27	3.56	23.3	24.7	26.1	26.4	23	26.5	26.4	26.1	25.8	25.5
28	3.62	23.1	24.5	26.4	26.4	23.3	26.6	26.5	26.4	25.9	25.2
29	3.61	23.4	24.6	26.4	26.3	24.4	26.5	26.5	26.5	25.8	25.1
30	3.66	23.4	24.6	26.4	26.3	24.1	26.6	26.5	26.4	25.8	25.2

Appendix 3: Experimental Data for effect of varying solvent flow rate with MEA-25wt%

Table 3a: Data recorded for flowrate=165.12 cc/min

			Temperature °C								
t/min	CO_2 (vol%)	Inlet T	A	B	C	D	E	F	G	H	Tank
0	12	23.8	24.4	25.4	24.9	24.6	25.4	25.5	25.7	25.7	23.9
1	10	23.1	24.5	25.3	24.8	24.7	26.2	25.7	25.7	25.6	23.8
2	9.66	23.1	24.5	25.3	24.8	25.4	26.1	26	25.7	25.6	23.6
3	8.56	22.9	24.4	25.6	25	25.4	26.9	26.1	25.8	25.6	23.6
4	7.23	23.1	24.8	25.7	24.7	25.8	26.9	26.3	25.9	25.8	23.9
5	6.5	23.1	24.6	25.6	24.8	26	27.2	26.4	26.1	25.9	23.1
6	6.42	23.1	23.6	25.5	24.9	25.6	27.3	26.6	26.1	25.8	23.9
7	5.78	23.1	23.7	25.7	24.6	25.6	27.4	26.5	26.3	25.8	23.5
8	5.62	22.8	24.3	25.8	24.7	25.8	27.5	26.7	26.4	25.9	23.9
9	5.31	23	24.7	25.9	25.4	25.9	27.5	26.8	26.5	26	23.9
10	4.76	22.8	24.3	25.7	25.4	25.8	27.4	26.9	26.7	25.8	23.7
11	4.21	22.8	24.7	25.9	25.8	25.8	27.3	27	26.8	25.7	23.9
12	4	22.8	24.8	25.8	26	25.9	27.8	27.1	26.9	25.6	24.1
13	3.94	23.1	24.8	25.8	25.6	26	27.4	27.3	26.9	25.5	24.3
14	3.62	23	24.9	25.9	25.6	25.8	28.1	27.4	27	25.7	24.2
15	3.12	23.1	25	26	25	25.7	28.2	27.5	27.1	25.6	24.1
16	2.9	23.4	24.5	26.1	25.9	25.6	28.4	27.8	27.2	25.8	24.2
17	2.76	23.1	24.8	25.9	26	25.5	28.4	27.7	27.2	25.7	24
18	2.55	23.3	24.9	25.8	26	25.7	28.3	27.7	27.3	25.7	24.1
19	2.42	23.2	24.7	25.8	26	25.6	28.2	27.9	27.4	25.6	24.2
20	2.44	23.3	24.6	25.9	26.1	25.8	28.1	27.8	27.4	25.6	24.3
21	2.54	23.1	24.5	25.7	26.2	25.7	28.2	27.7	27.2	25.8	24.1
22	2.52	23.4	24.6	25.6	26.3	25.7	28.1	27.6	27.2	25.7	24.3

23	2.5	23.1	24.7	25.4	26.1	25.8	28.2	27.5	27.3	25.7	24.1
24	2.53	23.3	24.5	25.4	26.3	25.6	27.5	27.4	27.3	25.8	24.2
25	2.51	23.2	24.8	25.4	26.3	25.7	27.4	27.6	27.3	25.8	24.3
26	2.51	23.1	24.5	25.7	26.2	25.7	28.0	27.7	27.2	25.8	24.1
27	2.52	23.4	24.6	25.6	26.3	25.7	28.0	27.6	27.2	25.7	24.3
28	2.52	23.1	24.7	25.4	26.1	25.8	28.0	27.5	27.3	25.7	24.1

Table 3b: Data recorded for flowrate=178.15cm^3/min

			Temperature °C								
t/min	CO_2 (vol%)	Inlet T	A	B	C	D	E	F	G	H	Tank
0	13.55	23.8	24.4	25.4	24.9	24.6	27.5	25.5	25.7	25.7	23.9
1	10.32	23.1	24.5	25.3	24.8	24.7	27.5	25.7	25.7	25.6	23.8
2	9.89	23.1	24.5	25.3	24.8	25.4	27.4	26	25.7	25.6	23.6
3	8.11	22.9	24.4	25.6	25	25.4	27.3	26.1	25.8	25.6	23.6
4	7.04	23.1	24.8	25.7	24.7	25.8	27.8	26.3	25.9	25.8	23.9
5	6.45	23.1	24.6	25.6	24.8	26	28.5	26.4	26.1	25.9	23.1
6	6.41	23.1	23.6	25.5	24.9	25.6	28.5	26.6	26.1	25.8	23.9
7	5.83	23.1	23.7	25.7	24.6	25.6	28.6	26.5	26.3	25.8	23.5
8	5.51	22.8	24.3	25.8	24.7	25.8	28.5	26.7	26.4	25.9	23.9
9	5.21	23	24.7	25.9	25.4	25.9	28.5	26.8	26.5	26	23.9
10	5.05	22.8	24.3	25.7	25.4	25.8	27.5	26.9	26.7	25.8	23.7
11	4.98	22.8	24.7	25.9	25.8	25.8	27.7	27	26.8	25.7	23.9
12	4.62	22.8	24.8	25.8	26	25.9	27.8	27.1	26.9	25.6	24.1
13	4.42	23.1	24.8	25.8	25.6	26	27.9	27.3	26.9	25.5	24.3
14	4.39	23	24.9	25.9	25.6	25.8	28	27.4	27	25.7	24.2
15	4.22	23.1	25	26	25	25.7	28.3	27.5	27.1	25.6	24.1
16	4.13	23.4	24.5	26.1	25.9	25.6	28.5	27.8	27.2	25.8	24.2

17	3.98	23.1	24.8	25.9	26	25.5	28.5	27.7	27.2	25.7	24
18	3.13	23.3	24.9	25.8	26	25.7	28.6	27.7	27.3	25.7	24.1
19	3.02	23.2	24.7	25.8	26	25.6	28	27.9	27.4	25.6	24.2
20	2.67	23.3	24.6	25.9	26.1	25.8	28.2	27.8	27.4	25.6	24.3
21	2.31	23.1	24.5	25.7	26.2	25.7	28.3	27.7	27.2	25.8	24.1
22	2.35	23.4	24.6	25.6	26.3	25.7	28.1	27.6	27.2	25.7	24.3
23	2.4	23.1	24.7	25.4	26.1	25.8	28	27.5	27.3	25.7	24.1
24	2.42	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2
25	2.42	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3

Table 3c: Data recorded for flowrate=236 cm^3/min

			Temperature °C								
t/min	CO_2 (vol%)	Inlet T	A	B	C	D	E	F	G	H	Tank
0	14.67	23.8	24.4	25.4	24.9	24.6	25.4	25.5	25.7	25.7	23.9
1	10.45	23.1	24.5	25.3	24.8	24.7	25.4	25.7	25.7	25.6	23.8
2	9.83	23.1	24.5	25.3	24.8	25.4	26.1	26	25.7	25.6	23.6
3	8.32	22.9	24.4	25.6	25	25.4	26.4	26.1	25.8	25.6	23.6
4	7.11	23.1	24.8	25.7	24.7	25.8	26.7	26.3	25.9	25.8	23.9
5	6.42	23.1	24.6	25.6	24.8	26	26.5	26.4	26.1	25.9	23.1
6	6.31	23.1	23.6	25.5	24.9	25.6	26.6	26.6	26.1	25.8	23.9
7	5.93	23.1	23.7	25.7	24.6	25.6	26.8	26.5	26.3	25.8	23.5
8	5.31	22.8	24.3	25.8	24.7	25.8	27.2	26.7	26.4	25.9	23.9
9	5.11	23	24.7	25.9	25.4	25.9	27.4	26.8	26.5	26	23.9
10	5.01	22.8	24.3	25.7	25.4	25.8	27.5	26.9	26.7	25.8	23.7
11	4.89	22.8	24.7	25.9	25.8	25.8	27.7	27	26.8	25.7	23.9
12	4.52	22.8	24.8	25.8	26	25.9	27.8	27.1	26.9	25.6	24.1
13	4.32	23.1	24.8	25.8	25.6	26	27.9	27.3	26.9	25.5	24.3

14	4.27	23	24.9	25.9	25.6	25.8	28	27.4	27	25.7	24.2
15	4.11	23.1	25	26	25	25.7	28.3	27.5	27.1	25.6	24.1
16	4.03	23.4	24.5	26.1	25.9	25.6	28.5	27.8	27.2	25.8	24.2
17	3.89	23.1	24.8	25.9	26	25.5	28.5	27.7	27.2	25.7	24
18	3.52	23.3	24.9	25.8	26	25.7	28.6	27.7	27.3	25.7	24.1
19	3.32	23.2	24.7	25.8	26	25.6	28	27.9	27.4	25.6	24.2
20	3.17	23.3	24.6	25.9	26.1	25.8	28.2	27.8	27.4	25.6	24.3
21	3.18	23.1	24.5	25.7	26.2	25.7	28.3	27.7	27.2	25.8	24.1
22	3.19	23.4	24.6	25.6	26.3	25.7	28.1	27.6	27.2	25.7	24.3
23	3.2	23.1	24.7	25.4	26.1	25.8	28	27.5	27.3	25.7	24.1
24	3.21	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2
25	3.21	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3

Appendix 4: Experimental Data for effect of varying solvent flow rate with MEA-20wt%

Table 4a: Data recorded for flowrate=169.17cm^3/min

			Temperature °C								
t/min	CO_2 (vol%)	Inlet T	A	B	C	D	E	F	G	H	Tank
0	11.45	23.8	24.4	25.4	24.9	24.6	25.7	25.5	25.7	25.7	23.9
1	9.01	23.1	24.5	25.3	24.8	24.7	26.9	25.7	25.7	25.6	23.8
2	8.43	23.1	24.5	25.3	24.8	25.4	26.7	26	25.7	25.6	23.6
3	8.15	22.9	24.4	25.6	25	25.4	27	26.1	25.8	25.6	23.6
4	7.9	23.1	24.8	25.7	24.7	25.8	27	26.3	25.9	25.8	23.9
5	6.67	23.1	24.6	25.6	24.8	26	27.1	26.4	26.1	25.9	23.1
6	6.21	23.1	23.6	25.5	24.9	25.6	27.2	26.6	26.1	25.8	23.9
7	5.78	23.1	23.7	25.7	24.6	25.6	27.4	26.5	26.3	25.8	23.5
8	5.1	22.8	24.3	25.8	24.7	25.8	27.3	26.7	26.4	25.9	23.9
9	5.25	23	24.7	25.9	25.4	25.9	27.3	26.8	26.5	26	23.9
10	4.89	22.8	24.3	25.7	25.4	25.8	27.5	26.9	26.7	25.8	23.7
11	4.41	22.8	24.7	25.9	25.8	25.8	27.7	27	26.8	25.7	23.9
12	4.12	22.8	24.8	25.8	26	25.9	27.8	27.1	26.9	25.6	24.1
13	3.89	23.1	24.8	25.8	25.6	26	27.9	27.3	26.9	25.5	24.3
14	3.51	23	24.9	25.9	25.6	25.8	28	27.4	27	25.7	24.2
15	3.21	23.1	25	26	25	25.7	28.3	27.5	27.1	25.6	24.1
16	2.98	23.4	24.5	26.1	25.9	25.6	28.5	27.8	27.2	25.8	24.2
17	2.84	23.1	24.8	25.9	26	25.5	28.5	27.7	27.2	25.7	24
18	2.75	23.3	24.9	25.8	26	25.7	28.6	27.7	27.3	25.7	24.1
19	2.78	23.2	24.7	25.8	26	25.6	28	27.9	27.4	25.6	24.2
20	2.51	23.3	24.6	25.9	26.1	25.8	28.2	27.8	27.4	25.6	24.3
21	2.31	23.1	24.5	25.7	26.2	25.7	28.3	27.7	27.2	25.8	24.1
22	2.11	23.4	24.6	25.6	26.3	25.7	28.1	27.6	27.2	25.7	24.3

23	2.13	23.1	24.7	25.4	26.1	25.8	28	27.5	27.3	25.7	24.1
24	2.14	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2
25	2.14	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3
26	2.12	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3
27	2.14	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2
28	2.11	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3

Table 4b: Data recorded for flowrate=180.17cm^3/min

		Temperature °C								
t/min	CO_2 (vol%)	Inlet T	A	B	C	D	E	F	G	H	Tank
0	14.32	23.8	24.4	25.4	24.9	24.6	25.7	25.5	25.7	25.7	23.9
1	11.82	23.1	24.5	25.3	24.8	24.7	26.9	25.7	25.7	25.6	23.8
2	10.32	23.1	24.5	25.3	24.8	25.4	26.7	26	25.7	25.6	23.6
3	9.78	22.9	24.4	25.6	25	25.4	27	26.1	25.8	25.6	23.6
4	9.21	23.1	24.8	25.7	24.7	25.8	27	26.3	25.9	25.8	23.9
5	8.78	23.1	24.6	25.6	24.8	26	27.1	26.4	26.1	25.9	23.1
6	8.24	23.1	23.6	25.5	24.9	25.6	27.2	26.6	26.1	25.8	23.9
7	7.82	23.1	23.7	25.7	24.6	25.6	27.4	26.5	26.3	25.8	23.5
8	7.56	22.8	24.3	25.8	24.7	25.8	27.3	26.7	26.4	25.9	23.9
9	7.14	23	24.7	25.9	25.4	25.9	27.3	26.8	26.5	26	23.9
10	6.92	22.8	24.3	25.7	25.4	25.8	27.5	26.9	26.7	25.8	23.7
11	6.98	22.8	24.7	25.9	25.8	25.8	27.7	27	26.8	25.7	23.9
12	6.81	22.8	24.8	25.8	26	25.9	27.8	27.1	26.9	25.6	24.1
13	6.72	23.1	24.8	25.8	25.6	26	27.9	27.3	26.9	25.5	24.3
14	6.14	23	24.9	25.9	25.6	25.8	28	27.4	27	25.7	24.2
15	5.93	23.1	25	26	25	25.7	28.3	27.5	27.1	25.6	24.1
16	5.31	23.4	24.5	26.1	25.9	25.6	28.5	27.8	27.2	25.8	24.2

17	4.89	23.1	24.8	25.9	26	25.5	28.5	27.7	27.2	25.7	24
18	4.7	23.3	24.9	25.8	26	25.7	28.6	27.7	27.3	25.7	24.1
19	4.13	23.2	24.7	25.8	26	25.6	28	27.9	27.4	25.6	24.2
20	3.74	23.3	24.6	25.9	26.1	25.8	28.2	27.8	27.4	25.6	24.3
21	3.62	23.1	24.5	25.7	26.2	25.7	28.3	27.7	27.2	25.8	24.1
22	3.54	23.4	24.6	25.6	26.3	25.7	28.1	27.6	27.2	25.7	24.3
23	3.52	23.1	24.7	25.4	26.1	25.8	28	27.5	27.3	25.7	24.1
24	3.53	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2
25	3.51	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3
26	3.52	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2
27	3.51	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3

Table 4c: Data recorded for flowrate=225.6 cm^3/min

		Temperature °C									
t/min	CO_2 (vol%)	Inlet T	A	B	C	D	E	F	G	H	Tank
0	16.73	23.8	24.4	25.4	24.9	24.6	25.7	25.5	25.7	25.7	23.9
1	14.73	23.1	24.5	25.3	24.8	24.7	26.9	25.7	25.7	25.6	23.8
2	12.89	23.1	24.5	25.3	24.8	25.4	26.7	26	25.7	25.6	23.6
3	12.52	22.9	24.4	25.6	25	25.4	27	26.1	25.8	25.6	23.6
4	12.04	23.1	24.8	25.7	24.7	25.8	27	26.3	25.9	25.8	23.9
5	11.93	23.1	24.6	25.6	24.8	26	27.1	26.4	26.1	25.9	23.1
6	11.42	23.1	23.6	25.5	24.9	25.6	27.2	26.6	26.1	25.8	23.9
7	10.98	23.1	23.7	25.7	24.6	25.6	27.4	26.5	26.3	25.8	23.5
8	10.32	22.8	24.3	25.8	24.7	25.8	27.3	26.7	26.4	25.9	23.9
9	9.45	23	24.7	25.9	25.4	25.9	27.3	26.8	26.5	26	23.9
10	9.11	22.8	24.3	25.7	25.4	25.8	27.5	26.9	26.7	25.8	23.7
11	9.04	22.8	24.7	25.9	25.8	25.8	27.7	27	26.8	25.7	23.9

12	8.91	22.8	24.8	25.8	26	25.9	27.8	27.1	26.9	25.6	24.1
13	8.45	23.1	24.8	25.8	25.6	26	27.9	27.3	26.9	25.5	24.3
14	8.04	23	24.9	25.9	25.6	25.8	28	27.4	27	25.7	24.2
15	7.91	23.1	25	26	25	25.7	28.3	27.5	27.1	25.6	24.1
16	7.53	23.4	24.5	26.1	25.9	25.6	28.5	27.8	27.2	25.8	24.2
17	7.12	23.1	24.8	25.9	26	25.5	28.5	27.7	27.2	25.7	24
18	7.04	23.3	24.9	25.8	26	25.7	28.6	27.7	27.3	25.7	24.1
19	6.94	23.2	24.7	25.8	26	25.6	28	27.9	27.4	25.6	24.2
20	6.8	23.3	24.6	25.9	26.1	25.8	28.2	27.8	27.4	25.6	24.3
21	6.72	23.1	24.5	25.7	26.2	25.7	28.3	27.7	27.2	25.8	24.1
22	6.59	23.4	24.6	25.6	26.3	25.7	28.1	27.6	27.2	25.7	24.3
23	6.05	23.1	24.7	25.4	26.1	25.8	28	27.5	27.3	25.7	24.1
24	5.72	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2
25	5.83	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3
26	5.69	23.4	24.6	25.6	26.3	25.7	28.1	27.6	27.2	25.7	24.3
27	5.64	23.1	24.7	25.4	26.1	25.8	28	27.5	27.3	25.7	24.1
28	5.62	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2
29	5.62	23.2	24.8	25.4	26.3	25.7	27.7	27.6	27.3	25.8	24.3
30	5.63	23.3	24.5	25.4	26.3	25.6	27.8	27.4	27.3	25.8	24.2

Appendix 5: Experimental data for mixtures of primary amine (MEA) and secondary amine (DEA)

Table 5a: Data recorded for DEA 25-wt% and MEA 6.4-wt% at solvent flowrate= 232.35 cm^3/min

			Temperature (oC)								
t/min	CO2 vol%	inlet G T	A	B	C	D	E	F	G	H	Tank
0	14	22.7	20.4	21.1	20.4	20.4	21.2	21.2	22	23.5	26.8
1	12.74	22.9	21.3	23.2	23.6	20.4	26.1	26.1	26.2	24.1	27
2	11.36	23	22.1	26.6	26.6	20.4	27.6	27.6	27.4	25.6	26.9
3	11.08	23	22.6	27.4	27.4	20.6	28.3	28.2	27.8	26.3	26.1
4	10.71	22.8	23.6	27.8	27.8	20.8	28.6	28.5	27.9	26.6	26.1
5	10.64	23.1	24.3	28.2	28.1	21.1	28.8	28.4	28.3	26.9	26.9
6	10.36	22.9	24.5	28	27.9	21.4	28.8	28.9	28.1	27.1	26.9
7	10.18	23.1	24.9	28.1	28	21.6	28.8	28.6	28.3	27.1	26.9
8	9.15	23	24.9	28.1	27.8	21.5	28.8	28.6	28.6	27.4	27.1
9	9	23.2	24.9	28	27.9	21.4	28.6	28.6	28.4	27.3	27.1
10	8.79	23.9	25	27.9	27.9	21.1	28.7	28.4	28.4	27.5	26.9
11	8.68	23.1	25	27.8	27.8	21.3	28.9	28.9	28.7	27.6	27
12	8.55	23.1	24.9	27.8	27.8	21.4	28.6	28.7	28.6	27.3	27.1
13	8.43	23.1	24.9	27.8	27.9	21.3	29.1	28.6	28.6	27.4	27.2
14	8.3	22.9	24.9	27.8	27.6	21.9	28.7	28.3	28.4	27.6	27.1
15	8.21	23.1	24.8	27.7	27.7	22	28.6	28.6	28.3	27.4	27.1
16	8.13	23.1	24.5	27.7	27.7	21.8	28.6	28.3	28.3	27.4	27.1
17	8.06	23.1	24.7	27.6	27.6	21.9	28.6	28.6	28.2	27.3	27.1
18	8.25	22.9	24.5	27.6	27.5	21.4	28.3	28.4	28.2	27.4	27
19	8.3	23	24.5	27.6	27.5	21.6	28.5	28.5	28.3	27.4	27.1
20	8.27	23.2	24.6	27.4	27.5	21.4	28.3	28.4	28.4	27.1	27.3
21	8.35	23.2	24.5	27.6	27.4	21.6	28.3	28.4	28.4	27.1	27.3

Table 5b: Data recorded for DEA 25-wt% and MEA 10.2-wt% at solvent flowrate= 200.98cm^3/min

			Temperature (oC)									
t/min	inlet T	CO2vol%	A	B	C	D	E	F	G	H	Solvent	Tank
0	22.7	14.6	22.2	22.5	22.4	22.3	22.3	22.7	23.1	22.7	27.8	26.7
1	22.8	11.67	22.8	27.3	27.2	21.8	28.2	28.1	27.9	25.3	27.9	25.8
2	23	10.5	23.6	28.7	28.7	21.4	29.3	29.1	28.6	26.7	26.8	28
3	22.9	10.01	24.3	29.2	29.2	21.4	29.8	29.5	29.1	27.4	27.7	28.1
4	22.7	9.66	24.7	29.4	29.4	21.9	29.8	29.8	29.4	27.6	25.9	28.1
5	22.8	9.21	25.1	29.3	29.3	21.9	29.9	29.9	29.4	28.1	27.9	28.2
6	22.8	8.79	25.4	29.3	29.3	21.4	29.9	30	29.4	28.4	26.5	28.3
7	23	8.43	25.6	29.1	29.1	21.3	29.9	30	29.7	28.3	28.2	28.2
8	22.8	8.08	25.8	29.4	29.4	21.7	30	30	29.5	28.6	27.5	28.4
9	23	7.9	25.6	29.3	29.3	21.6	29.9	30	29.5	28.5	27.8	28.3
10	23.1	7.68	25.8	29.1	29.1	21.3	30.1	30.1	29.8	28.8	27.8	28.4
11	23	7.5	25.8	29.2	29.2	21.4	30	30.1	29.5	29.1	28.8	28.4
12	23.1	7.31	25.8	29.2	29.3	21.7	30.1	30	29.6	29	28.9	28.4
13	23.3	7.11	26	29.3	29.3	22	30.4	30.3	29.9	29.1	28.4	28.4
14	23.1	6.89	25.9	29.3	29.3	21.8	30.2	30.4	30	29.3	28.8	28.5
15	23.1	6.61	26	29.2	29.2	21.7	30.2	30.1	30.1	29.3	28.3	28.7
16	23.2	6.46	25.9	29.1	29.1	21.8	30.3	30.3	30.1	29.4	28.8	28.5
17	23.2	6.21	26	28.9	29	21.8	30.2	30.1	30.1	29.3	29.2	28.6
18	23.2	6.01	26	28.9	28.9	21.6	30.1	30.2	30	29.4	29.3	28.6
19	23.1	5.81	26	28.9	28.9	21.7	30.2	30.2	30	29.3	27.9	28.5
20	23.2	5.64	25.9	28.9	29	21.5	30.2	30.5	30	29.4	28.3	28.7
21	23.1	5.4	26.1	28.9	28.9	21.3	30.3	30.2	30	29.3	28.4	28.4
22	23.1	5.2	26.1	28.8	28.8	21.3	30.2	30	30	29.5	29.1	28.6
23	23.2	4.93	25.9	28.8	28.8	21.3	30	30	30.1	29.5	28.1	28.4

24	23.2	4.64	26.1	28.6	28.6	20.9	30	30.1	30.1	29.4	28.6	28.5
25	23.2	4.41	26.1	28.6	28.6	21.2	29.9	30	29.9	29.4	29.5	28.6
26	23.1	4.18	25.9	28.4	28.4	20.9	29.9	29.9	30	29.5	29.1	28.4
27	23.2	4.03	26	28.5	28.5	20.9	29.9	30	29.9	29.6	29.1	28.4
28	23.2	3.84	25.9	28.4	28.5	21.1	30.1	30	30	29.7	28.9	28.4
29	23.1	3.58	25.9	28.3	28.3	21.1	29.9	29.9	29.9	30.2	29.4	28.6
30	23.2	3.42	25.8	28.3	28.3	21	29.8	29.9	29.9	29.6	28.3	28.4
31	23.2	3.23	25.8	28.3	28.1	20.9	29.6	29.6	30	29.6	29.3	28.3
32	23.1	3.35	25.6	28.4	28.3	21.1	29.8	29.6	29.8	29.5	28.7	28.4
33	23.1	3.4	25.6	28.3	28.1	20.9	29.6	29.5	30	29.5	28.9	28.3
34	23.2	3.38	25.7	28.3	28.1	20.9	29.6	29.6	29.9	29.5	28.7	28.4
35	23.1	3.31	25.6	28.4	28.3	20.7	29.6	29.6	29.9	29.6	28.8	28.3
36	23.1	3.37	25.6	28.3	28.3	21.1	29.7	29.7	29.8	29.5	28.6	28.3
37	23.1	3.35	25.6	28.3	28.2	20.8	29.6	29.6	29.8	29.5	28.7	28.4

Appendix 6: Data for total moles CO_2 absorbed and mol CO_2/ mL of solvent for mixed amine (MEA+DEA)

Table 6a: Data for DEA-25wt% + MEA-10.2wt%

co2 vol%	t/min	mol co2	Absorbed Co2	mol co2/ mL solvent
14.600	0.000	0.040	0.000	0.000000
11.670	1.000	0.032	0.008	0.000040
10.500	2.000	0.029	0.011	0.000056
10.010	3.000	0.028	0.013	0.000063
9.660	4.000	0.027	0.014	0.000068
9.210	5.000	0.025	0.015	0.000074
8.790	6.000	0.024	0.016	0.000080
8.430	7.000	0.023	0.017	0.000085
8.080	8.000	0.022	0.018	0.000089
7.900	9.000	0.022	0.018	0.000092
7.680	10.000	0.021	0.019	0.000095
7.500	11.000	0.021	0.020	0.000097
7.310	12.000	0.020	0.020	0.000100
7.110	13.000	0.020	0.021	0.000103
6.890	14.000	0.019	0.021	0.000106
6.610	15.000	0.018	0.022	0.000110
6.460	16.000	0.018	0.022	0.000112
6.210	17.000	0.017	0.023	0.000115
6.010	18.000	0.017	0.024	0.000118
5.810	19.000	0.016	0.024	0.000121
5.640	20.000	0.016	0.025	0.000123
5.400	21.000	0.015	0.025	0.000126
5.200	22.000	0.014	0.026	0.000129
4.930	23.000	0.014	0.027	0.000133
4.640	24.000	0.013	0.027	0.000137
4.410	25.000	0.012	0.028	0.000140
4.180	26.000	0.011	0.029	0.000143
4.030	27.000	0.011	0.029	0.000145
3.840	28.000	0.011	0.030	0.000147
3.580	29.000	0.010	0.030	0.000151
3.420	30.000	0.009	0.031	0.000153
3.230	31.000	0.009	0.031	0.000156
3.350	32.000	0.009	0.031	0.000154
3.400	33.000	0.009	0.031	0.000153
3.380	34.000	0.009	0.031	0.000154
3.310	35.000	0.009	0.031	0.000155
3.370	36.000	0.009	0.031	0.000154
3.350	37.000	0.009	0.031	0.000154

Table 6b: Data for DEA-25wt% + MEA-6.4 wt%

co2 vol%	l/min	mol co2	Absorbed Co2	mol co2/mL solvent
0.000	14.000	0.037	0.000	0.000000
1.000	12.740	0.034	0.006	0.000025
2.000	11.360	0.030	0.010	0.000041
3.000	11.080	0.030	0.010	0.000044
4.000	10.710	0.029	0.011	0.000049
5.000	10.640	0.028	0.012	0.000049
6.000	10.360	0.028	0.012	0.000053
7.000	10.180	0.027	0.013	0.000055
8.000	9.150	0.024	0.016	0.000067
9.000	9.000	0.024	0.016	0.000068
10.000	8.790	0.024	0.016	0.000071
11.000	8.680	0.023	0.017	0.000072
12.000	8.550	0.023	0.017	0.000073
13.000	8.430	0.023	0.017	0.000075
14.000	8.300	0.022	0.018	0.000076
15.000	8.210	0.022	0.018	0.000077
16.000	8.130	0.022	0.018	0.000078
17.000	8.060	0.022	0.018	0.000079
18.000	8.250	0.022	0.018	0.000077
19.000	8.300	0.022	0.018	0.000076
20.000	8.270	0.022	0.018	0.000077
21.000	8.350	0.022	0.018	0.000076

Appendix 7: Data for total moles CO_2 absorbed and mol CO_2/ mL of solvent for MEA at maximum flowrate

Table 7a: Data for MEA-30wt%

co2 Vol%	L/min	mol co2	Absorbed Co2	mol co2/ mL solvent
0	17	0.036653	0.000000	0.000000
1	11.2	0.024148	0.012502	0.000057
2	6.8	0.014661	0.021989	0.000100
3	5.4	0.011643	0.025007	0.000114
4	5.3	0.011427	0.025223	0.000115
5	4.9	0.010565	0.026085	0.000119
6	4.93	0.010629	0.026021	0.000118
7	4.92	0.010608	0.026042	0.000119
8	4.68	0.010090	0.026560	0.000121
9	4.62	0.009961	0.026689	0.000121
10	4.57	0.009853	0.026797	0.000122
11	4.43	0.009551	0.027099	0.000123
12	4.28	0.009228	0.027422	0.000125
13	4.17	0.008991	0.027659	0.000126
14	4.2	0.009055	0.027595	0.000126
15	4.3	0.009271	0.027379	0.000125
16	4.25	0.009163	0.027487	0.000125
17	4.19	0.009034	0.027616	0.000126
18	4.12	0.008883	0.027767	0.000126
19	4.05	0.008732	0.027918	0.000127
20	3.96	0.008538	0.028112	0.000128
21	3.81	0.008215	0.028435	0.000129
22	3.75	0.008085	0.028565	0.000130
23	3.66	0.007891	0.028759	0.000131
24	3.64	0.007848	0.028802	0.000131
25	3.62	0.007805	0.028845	0.000131
26	3.57	0.007697	0.028953	0.000132
27	3.56	0.007676	0.028974	0.000132
28	3.62	0.007805	0.028845	0.000131
29	3.61	0.007783	0.028867	0.000131
30	3.66	0.007891	0.028759	0.000131

Table 7b: Data for MEA-25wt%

co2 vol%	t/min	mol co2	Absorbed Co2	mol co2/ ml solvent
0.000	14.670	0.033321	0.000000	0.000000
1.000	10.450	0.023736	0.009564	0.000041
2.000	9.830	0.022328	0.010972	0.000046
3.000	8.320	0.018898	0.014402	0.000061
4.000	7.110	0.016149	0.017151	0.000073
5.000	6.420	0.014582	0.018718	0.000079
6.000	6.310	0.014332	0.018968	0.000080
7.000	5.930	0.013469	0.019831	0.000084
8.000	5.310	0.012061	0.021239	0.000090
9.000	5.110	0.011607	0.021693	0.000092
10.000	5.010	0.011380	0.021920	0.000093
11.000	4.890	0.011107	0.022193	0.000094
12.000	4.520	0.010267	0.023033	0.000098
13.000	4.320	0.009812	0.023488	0.000100
14.000	4.270	0.009699	0.023601	0.000100
15.000	4.110	0.009335	0.023965	0.000102
16.000	4.030	0.009154	0.024146	0.000102
17.000	3.890	0.008836	0.024464	0.000104
18.000	3.520	0.007995	0.025305	0.000107
19.000	3.320	0.007541	0.025759	0.000109
20.000	3.170	0.007200	0.026100	0.000111
21.000	3.180	0.007223	0.026077	0.000110
22.000	3.190	0.007246	0.026054	0.000110
23.000	3.200	0.007268	0.026032	0.000110
24.000	3.210	0.007291	0.026009	0.000110
25.000	3.210	0.007291	0.026009	0.000110

Table 7c: Data for MEA-20wt%

co2 vol%	t,min	mol co2	Absorbed Co2	mol co2/ml solvent
0	16.73	0.029989	0.000000	0.000000
1	14.73	0.026404	0.003586	0.000016
2	12.89	0.023106	0.006884	0.000031
3	12.52	0.022442	0.007548	0.000033
4	12.04	0.021582	0.008408	0.000037
5	11.93	0.021385	0.008605	0.000038
6	11.42	0.020471	0.009519	0.000042
7	10.98	0.019682	0.010308	0.000046
8	10.32	0.018499	0.011491	0.000051
9	9.45	0.016939	0.013051	0.000058
10	9.11	0.016330	0.013660	0.000061
11	9.04	0.016204	0.013786	0.000061
12	8.91	0.015971	0.014019	0.000062
13	8.45	0.015147	0.014843	0.000066
14	8.04	0.014412	0.015578	0.000069
15	7.91	0.014179	0.015811	0.000070
16	7.53	0.013498	0.016492	0.000073
17	7.12	0.012763	0.017227	0.000076
18	7.04	0.012619	0.017371	0.000077
19	6.94	0.012440	0.017550	0.000078
20	6.8	0.012189	0.017801	0.000079
21	6.72	0.012046	0.017944	0.000080
22	6.59	0.011813	0.018177	0.000081
23	6.05	0.010845	0.019145	0.000085
24	5.72	0.010253	0.019737	0.000087
25	5.83	0.010450	0.019540	0.000087
26	5.69	0.010199	0.019791	0.000088
27	5.64	0.010110	0.019880	0.000088
28	5.62	0.010074	0.019916	0.000088
29	5.62	0.010074	0.019916	0.000088
30	5.63	0.010092	0.019898	0.000088